ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

MODELLING OF MODIFIED ACTIVATED SLUDGE SYSTEMS FOR EXCESS SLUDGE REDUCTION

M.Sc. THESIS

Buşra ALLI

Department of Environmental Engineering

Environmental Biotechnology Programme

DECEMBER 2016

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

MODELLING OF MODIFIED ACTIVATED SLUDGE SYSTEMS FOR EXCESS SLUDGE REDUCTION

M.Sc. THESIS

Buşra ALLI
501141801

Department of Environmental Engineering

Environmental Biotechnology Programme

Thesis Advisor: Prof. Dr. Seval SÖZEN

DECEMBER 2016

ISTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

ÇAMUR AZALTIMINA YÖNELİK MODİFİYE AKTİF ÇAMUR SİSTEMLERİNİN MODELLENMESİ

YÜKSEK LİSANS TEZİ

Buşra ALLI
501141801

Çevre Mühendisliği Anabilim Dalı

Çevre Biyoteknolojisi Programı

Tez Danışmanı: Prof. Dr. Seval SÖZEN

ARALIK 2016

Buşra Allı, a M.Sc. student of ITU Graduate School of Science Engineering and Technology student ID 501141801, successfully defended the thesis entitled "MODELLING OF MODIFIED ACTIVATED SLUDGE SYSTEMS FOR EXCESS SLUDGE REDUCTION", which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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

Jury Members : **Doç. Dr. H. Güçlü İNSEL**
İstanbul Technical University

Prof. Dr. Ayşen ERDİNÇLER
Boğaziçi University

Date of Submission : 25 November 2016
Date of Defense : 21 December 2016

to my family,

FOREWORD

I would like to express my sincere gratitude to my supervisor Prof. Dr. Seval SÖZEN for her valuable leadership, support and patience throughout this thesis study. I am thankful to her for scientific guidance and life-long advices since the day we met.

I would like to thank to the greatest mentor, Prof. Dr. Derin ORHON, for his worthful comments and advices. It was a great chance for me to work with him, I learned a lot and I will continue to learn from him.

I am also grateful to Assoc. Prof. Dr. Güçlü İNSEL for his meritorious support and expertise during my study.

I would also like thank to Cansu KARACA for her friendship and support. She created a friendly and joyful environment for me.

Special thanks to my best friend, Ozan Merter BİNGÖL, for his love, motivational support and patience.

I would like to express my deepest appreciation to my family; my parents Erdinç ALLI and Serpil ALLI and also my brother Mertcan ALLI for their continuous love, belief and support. I wish to dedicate this thesis to my dear family.

November 2016

Buşra ALLI
(Environmental Engineer)

TABLE OF CONTENTS

ABBREVIATIONS

ASM	: Activated Sludge Model
CAS	: Conventional Activated Sludge
COD	: Chemical Oxygen Demand
CR	: Contact Reactor
CS	: Contact Stabilization
CSTR	: Completely Stirred Reactor
HRT	: Hydraulic Retention Time
IWA	: International Water Association
OSA	: Oxic-Settling-Anaerobic
OUR	: Oxygen Uptake Rate
SR	: Stabilization Reactor
SRT	: Sludge Retention Time
VFA	: Volatile Fatty Acid
VSS	: Volatile Suspended Solids
WWTP	: Wastewater Treatment Plant

LIST OF TABLES

LIST OF FIGURES

MODELLING OF MODIFIED ACTIVATED SLUDGE SYSTEMS FOR EXCESS SLUDGE REDUCTION

SUMMARY

Nowadays active sludge process is one of the most widely used processes among biological wastewater treatment systems not only for domestic but also for industrial wastewater treatment. The activated sludge process has undergone many changes from its discovery to today and has been modified and used for certain wastewater characterizations.

In the activated sludge process, a portion of the organic matter in the wastewater is removed from the medium by conversion to water and carbon dioxide while the rest is turned into a by-product and formed so called “sewage sludge”. Due to the high organic matter and water content in the formed sewage sludge, it is forced to be treated and disposed rather than be removed directly from the system.

Sludge treatment and disposal is a costly process that must be carried out in accordance with the environmental obligations. The cost of sludge treatment and disposal is about 50-60% of total operating cost of biological treatment systems. The amount of sludge is related to the configuration of the activated sludge system and the sludge retention time. The generally applied sludge treatment procedure is based on collecting the sludge at the outlet of the activated sludge system and reducing the amount of water by thickening reactor. After thickening, the stabilization process is applied in order to reduce the content of organic matter and the sewage sludge is finally adapted to the its ultimate final disposal alternative after dewatering process. Stabilization can be carried out in either aerobic or anaerobic conditions. Stabilization is described as one of the separate or post-process sludge treatments.

The use of technological approaches to reduce the amount of sludge “in process” without significantly increasing operating costs has great importance from an operational point of view. The sludge reduction which is carried out in aeration tank is one of the implementations of “in process sludge reduction mechanisms” in the small activated sludge systems. Contact stabilization (CS) has been applied mainly in-process sludge treatment system and oxic-settling-anaerobic (OSA) systems is currently used in-process sludge treatment and disposal alternative. Unlike the activated sludge systems where the sludge treatment is made out of the process, in these systems the sludge stabilization is ensured in the same volume and the system is operated more efficiently and less sludge production is ensured.

The purpose of this thesis is to determine the effect of in-process sludge stabilization on the sludge formation. In this context, OSA and CS systems which are fed with domestic wastewater evaluated within the framework of modern environmental biotechnology modeling approach by using AQUASIM software.

The OSA system is a modification of the conventional activated sludge system. The wastewater is primarily aerated in an aerobic tank and then settled. While the upper phase of the sedimentation tank is being discharged from the system in the OSA process, a portion of the sewage sludge is directly recycled to the aeration tank to form the recycle of the activated sludge system. The rest of the sludge portion is then anaerobically stabilized. The stabilized sludge in the anaerobic stabilization tank is fed back into the aeration tank. The OSA system is operated as a system without discharging the sewage sludge. In the modelling approach, the anaerobic stabilization system is excluded and the biomass from OSA system is indicated as the input as a recycle aerobic reactor.

Contact stabilization is a modification of the rapidly operated activated sludge system. The wastewater is first fed to the contact reactor which is aerated very shortly, and then it is transmitted to the settling tank. While the upper phase of the sedimentation tank leaves the system, the sludge that has been sedimented is transferred to the stabilization reactor for re-aeration. The stabilized sludge is fed back into the contact reactor. The basic principle of the contact stabilization process is to reduce the amount of sewage sludge by achieving rapid biological treatment and carrying out adsorption in the reactor via transferring sewage sludge to the stabilization reactor including particulate organic matter.

In the context of this thesis, three different activated sludge configurations, CAS, OSA and CS, were evaluated in terms of sludge production by conducting a modeling study using AQUASIM software for carbon removal. All systems were scrutinized under different operational conditions to identify the effect of system configuration on the production of excess sludge. CAS was considered as a control system to predict the improvement in excess sludge production.

The model for the CAS system was first run for an HRT of 8 hours (3350 m^3 volume) to characterize the common operational conditions of a CAS. Then HRT was reduced to 5 hours (2100 m^3 volume) to demonstrate the limitation of system operation due to the settling conditions.

As expected from a CAS process, the sludge generation was decreased enormously when the sludge age was increased from 6 to 15 days. This was actually the reason for operating the activated sludge systems at an extended mode. It should be noted that high SRT, as 15 days, ended up with the lowest active biomass concentration as a result of the dominant endogenous respiration. Results showed that the increase of the sludge age from 6 days to 15 days reduced the total sludge production approximately 25%, and the meaningful reduction was in the active biomass with a level of 50%, where a remarkable stabilization of organic matter was observed for both 8 hours and 5 hours HRT. It is obvious that increasing the SRT and decreasing HRT as an operational parameter have a limitation due to the feasibility reasons. It seems only applicable to small treatment plants, where the sludge is aerobically stabilized within the activated sludge system.

Modeling for OSA system reflected the features of the classical activated sludge system with an initial active biomass. The volume of the reactor was selected as 3350 m^3 yielding an HRT of 8 hours (0.335 days).

In OSA process, an input of 50 gr cell COD/m^3 in the influent was sufficient to yield a 75% reduction, whereas a 100 gr cell COD/m^3 ended up approximately with a 100% reduction. In this case, the wasted sludge consisted of only the initial biomass load (Q X_{H1}). The results of the simulation proved that enhanced endogenous decay due to higher active biomass level sustained in the OSA reactor should be regarded as the major cause of excess sludge reduction in the OSA system. In summary, for the studied OSA system, the simulations show that 8 d SRT and 200 gr cell COD/m3 XH1 influx would be enough to stop biomass generation which is not comparable level achieved in a CAS process that operated at 8 days.

CS system was designed to have a CR with a very short HRT at a very small volume aiming only the removal of soluble substrate and an aerobic reactor added in the recirculation line to examine the possible effect on the sludge reduction. First, the system was designed to be compared to the operational conditions of CAS by selecting a similar total HRT of 8 hours, where a very short HRT of 45 minutes was allocated to CR. The volumes were adjusted to 300 m3 for CR and 3000 m3 for SR, as a total of 3300 m3. In the second run, the total HRT was reduces to 5 hours to outline the effect of system behaviour on the sludge production. The HRT was divided as 30 minutes and 4.5 hours to CR and SR, respectively. In this case the total volume was reduced to 2100 m3, shared as 200 m3 by CR, 1900 m3 by SR.

First of all, the CS process with two different HRTs were compared in terms of the sludge production. They were compared with CAS to evaluate the extent of sludge reduction of both configurations. CS process with the total HRTs of 5 hours and 8 hours were compared with CAS with an HRT of 8 hours in terms of the sludge production. HRT for 5 hours was not considered in the evaluation with the fact that the produced mass in the reactor cannot be settled in the conventional settling tank due to the solid flux limitation.

The total sludge production, in other words the excess sludge to be further treated in a sludge treatment facility was found approximately the same for CAS with an HRT of 8 hours compared to CS with HRTs of 8 and 5 hours. The reason of having mostly the same sludge amount in CAS and CS araised from the fact that the amount of sludge remained the same in CS as a result of the raised concentration in the decreased volume. Namely, decreasing the HRT was increasing the concentration of the particulates yielding the generation of the same amount of sludge at significantly lower volumes.

As a future perspective, the modifications of activated sludge systems for the sludge reduction may be developed/improved in conducting experimental studies within the view of modelling studies.

ÇAMUR AZALTIMINA YÖNELİK MODİFİYE AKTİF ÇAMUR SİSTEMLERİNİN MODELLENMESİ

ÖZET

Günümüzde gerek evsel gerekse endüstriyel atıksuların arıtılmasında en yaygın kullanılan biyolojik arıtma sistemi, aktif çamur prosesidir. Aktif çamur prosesi, keşfinden bugüne kadar birçok değişikliğe uğramış ve belirli karakterdeki atıksular için modifiye edilerek kullanılmıştır. Aktif çamur prosesinde atıksu içerisindeki organik maddenin bir kısmı, su ve karbondioksite dönüştürülerek ortamdan uzaklaştırılırken bir kısmı da "çamur" adı verilen bir yan ürüne dönüşmektedir. Oluşan bu çamurun içerisindeki yüksek organik madde ve su içeriği nedeniyle doğrudan uzaklaştırılması mümkün değildir, arıtılması ve bertaraf edilmesi zorunludur. Çamur arıtımı ve bertarafı, çevresel yükümlülüklere uygun olarak gerçekleştirilmesi gereken yüksek maliyetli bir işlemdir. Biyolojik arıtma sistemlerinde çamur arıtma ve bertaraf maliyeti toplam işletme giderlerinin yaklaşık %50-60'ını oluşturmaktadır.

Çamur miktarı aktif çamur sisteminin konfigürasyonu ve çamur bekletme süresi ile ilişkilidir. Genel olarak uygulanan çamur arıtma prosedürü çamurun aktif çamur sistemi çıkışında toplanarak yoğunlaştırma işlemi ile su miktarının azaltılması, sonrasında organik madde içeriğini azaltmak üzere stabilizasyon işleminin uygulanması ve susuzlaştırma işleminden geçirilerek nihai uzaklaştırma alternatiflerinden birine uygun hale getirmektir. Stabilizasyon aerobik veya anaerobik koşullarda yapılabilmektedir. Bu uygulama ayrı ya da proses sonrası çamur arıtımı olarak nitelendirilmektedir.

Çamur miktarının işletme giderlerini çok arttırmadan proses içerisinde azaltılmasına yönelik teknolojik yaklaşımların kullanımı operasyonel açıdan büyük önem taşımaktadır. Küçük aktif çamur sistemlerinde çamur stabilizasyonunun havalandırma havuzu içerisinde yapılması bu yaklaşımın basit bir uygulamasıdır. Geçmişte, kontakt stabilizasyon (KS), günümüzde ise oksik-çöktürme-anaerobik (OÇA) sistemler proses içi çamur arıtımı ve bertarafına yönelik olarak kullanılan sistemlerin başlıcalarıdır. Bu sistemlerde, özellikle çamur arıtımının proses dışı yapıldığı aktif çamur sistemlerinden farklı olarak, aynı hacim içerisinde çamur stabilizasyonu sağlanarak hem sistemin daha verimli çalışması sağlanır hem de daha az çamur üretimi sağlanır.

Bu tez çalışması ile proses içi çamur stabilizasyonunun çamur oluşumuna etkisinin belirlenmesi amaçlanmıştır. Bu kapsamda evsel nitelikli atıksu ile beslenen oksik-çöktürme-anaerobik (OÇA) ve kontakt stabilizasyon sistemleri, AQUASIM yazılımı kullanılmak suretiyle günümüz modern çevre biyoteknolojisi modelleme yaklaşımı çerçevesinde değerlendirilmiştir.

Oksik-çöktürme-anaerobik (OÇA) sistemi konvansiyonel aktif çamur sisteminin bir modifikasyonudur. Atıksu öncelikle bir aerobik tankta havalandırılmakta ve sonrasında çöktürülmektedir. OÇA prosesinde çöktürme tankının üst fazı sistemden

deşarj edilirken, çöken çamurun bir kısmı doğrudan aktif çamur sistemi geri devrini oluşturmak üzere havalandırma tankına geri devrettirilmekte, kalan kısmı da anaerobik stabilizasyona tabi tutulmaktadır. Anaerobik stabilizasyon havuzunda stabilize olan çamur ise yeniden havalandırma tankına beslenmektedir. OÇA sistemi çamur çıkışı olmayan bir sistem olarak işletilmektedir. Modelleme yaklaşımında aerobik olarak işletilen aktif çamur sisteminde oluşan çamurun stabilize edildiği anaerobik stabilizasyon sistemi kapsam dışında tutulmuş, bu sistemin çıkışından yapılan biyokütle geri devri aerobik reaktöre temsili aktif biyokütle girişi ile gösterilmiştir.

Kontakt stabilizasyon hızlı işletilen aktif çamur sisteminin bir modifikasyonudur. Atıksu ilk olarak çok kısa süreli havalandırılan kontakt reaktörüne beslenmekte, daha sonra çöktürme tankına gönderilmektedir. Çöktürme tankının üst fazı sistemi terk ederken, çöken çamur yeniden havalandırılmak üzere stabilizasyon reaktörüne devrettirilmektedir. Burada stabilize edilen çamur yeniden kontakt reaktörüne geri beslenmektedir. Kontakt stabilizasyon prosesinin temel prensibi kontakt reaktöründe hızlı bir biyolojik arıtma ve adsorpsiyonun gerçekleşmesi, partiküler organik madde ve oluşan çamurun aerobik stabilizasyon reaktöründe giderilerek toplam çamur miktarının sistem bütününde azaltılmasının sağlanmasıdır.

Bu çalışma kapsamında konvansiyonel aktif çamur sistemi, oksik-çöktürme-anaerobik prosesi ve kontakt stabilizasyon prosesleri modelleme yaklaşımı çerçevesinde değerlendirilmiştir. Modelleme çalışmaları, belirtilen bu üç sistem için 6, 8, 10, 12 ve 15 gün çamur bekletme süreleri kullanılarak yürütülmüş, ve bu sistemler çamur üretimi açısından değerlendirilmiştir.

Konvansiyonel aktif çamur sistemi, çamur üretimi açısından karşılaştırma yapmak amacıyla incelenmiştir. Bu sistem 3350 m^3 ve 2100 m^3 olmak üzere iki farklı hacimde, hidrolik bekletme süreleri 8 saat ve 5 saat olacak şekilde çalıştırılmıştır. 8 saat, günümüzde bu sistem için yaygın olarak kullanılan hidrolik bekletme süresini yansıtırken, 5 saatlik hidrolik bekletme süresi sistemin limitasyonlarını görebilmek amacıyla kullanılmıştır. Gerekli geri devir ve atık çamur debisi her çamur yaşına uygun olarak hesaplanmıştır.

Konvansiyonel sistemden beklendiği üzere, çamur yaşının 6 günden 15 güne çıkması ile toplam çamur üretimi büyük bir ölçüde azalmıştır. Çamur yaşı 15 gün ile çalışan sistemin çamur üretimi en düşük seviyede olup, uzun havalandırmalı aktif çamur sistemine benzer şekilde çalıştığı saptanmıştır. Çamur yaşının 15 güne kadar çıkması, içsel solunum oranının baskın olmasından kaynaklanan en az çamur üretimini göstermektedir.

OÇA prosesinde çamur üretimi iki parametre ile değerlendirilmiştir: Bunlar çamur yaşı ve sistemin girişine beslenen aktif biyokütledir. OÇA prosesi, bu tez çalışması kapsamında konvansiyonel aktif çamur sisteminin prensipleri doğrultusunda modelleme için basitleştirilmiş, sistemin giriş akımına yapılan aktif biyokütle beslemesi ile değerlendirilmiştir. Bu basitleştirme, OÇA prosesinden çıkan fazla çamurun başka bir yerde stabilize olarak sistemin girişine geri döndüğü kabulüne dayanmaktadır. Bu sistem, hidrolik bekletme süresi 8 saat olan, 3350 m^3 reaktör hacmi kullanılarak tasarlanmıştır. 6 ile 15 gün arasında değişen çamur yaşları için, sistemin girişine 50, 100, 150 ve 200 gr KOİ/m^3 aktif biyokütle girişi yapılmış, üretilen çamur miktarları incelenmiştir. Değişen çamur yaşlarına uygun olarak geri devir ve atık çamur debileri belirlenmiştir.

OÇA sisteminin modelleme sonuçlarına göre, sisteme 200 gr hücre KOİ/m^3 aktif biyokütle girişi ile çamur yaşı 8 gün ve sonrasında net çamur oluşumu negatif değerler almıştır. Sistemde biriken biyokütle sonucunda, içsel solunum seviyesinin çoğalma seviyesi ile karşılaştırıldığında büyük oranda artış gösterdiği saptanmıştır. Aynı etki, 150 gr hücre KOİ/m^3 aktif biyokütle girişi ile çamur yaşı 10 gün ve sonrasında da sistem performansına yansıyarak, net çamur oluşumunun negatife düşmesine neden olmuştur.

OÇA sistemi konvansiyonel sistem ile karşılaştırıldığında, toplam çamur üretimin önemli oranda azaldığı saptanmıştır. Çamur yaşının 6 günden 15 güne kadar çıkması ile sistemin girişine yapılan 50 ile 200 gr hücre KOİ/m^3 aktif biyokütle beslemesi, toplam çamur oluşumun önemli ölçüde azalmasına hatta net üretimin negatife düşmesine sebep olmuştur.

KS sistemi; çok küçük bir hacimde çok kısa bir hidrolik bekletme süresine sahip, sadece çözünebilir substratın giderildiği bir kontakt tank ve çamur azaltımındaki olası etkilerini incelemek üzere geri devir hattında bulunan bir satbilizasyon tankından oluşmaktadır. Öncelikle, konsanviyonel sistemle işletme koşulları açısından karşılaştırma yapabilmek amacıyla higrolik bekletme süresi, 45 dakikası kontakt tanka ait olmak üzere toplam 8 saat olarak seçilmiştir. Reaktör hacimleri 300 m^3 kontakt ve 3000 m^3 stabilizasyon tankı olmak üzere toplam 3300 m^3 olarak belirlenmiştir. İkinci modelleme, sistemin çamur üretim performansındaki değişkliği görmek üzere hidrolik bekletme süresi 5 saate indirilerek yapılmıştır. Toplam hidrolik bekletme süresi 30 dakika ve 4.5 saat olacak şekilde sırasıyla kontakt ve stabilizasyon tanklarına dağıtılmıştır.

Öncelikle iki farklı hidrolik bekletme ile KS prosesi çamur üretimi açısından karşılaştırılmıştır. Daha sonra, her iki KS konfigürasyonu çamur azalma oranının değerlendirilmesi amacıyla konvansiyonel sistem ile karşılaştırılmıştır. Toplam hidrolik bekletme süreleri 5 saat ve 8 saat olan KS prosesi, çamur üretimi bakımından 8 saatlik hidrolik bekletmeye sahip konvansiyonel sistem ile karşılaştırılmıştır. Değerlendirmede, reaktörde üretilen kütlenin klasik çöktürme tankında çökelemeyeceği öngörülerek 5 saat hidrolik bekletmeli konvansiyonel sistem dikkate alınmamıştır.

Toplam çamur üretimi, başka bir deyişle çamur arıtma tesisinde daha fazla arıtılması gereken fazla çamur, 8 saatlik konvansiyonel sistem ile 8 saatlik ve 5 saatlik kontakt stabilizasyon sistemine göre yaklaşık olarak aynı oranda bulunmuştur. Konvansiyonel ve kontakt stabilizasyon sistemlerinde çoğunlukla aynı çamur miktarının bulunmasının nedeni, kontakt stabilizasyonda azaltılmış hacimde konsantrasyonun artması nedeniyle üretilen çamur miktarının aynı olmasıdır. Yani, hidrolik bekletme süresinin azaltılması, daha düşük hacimde partiküler maddenin daha konsantre olmasıyla, aynı miktarda çamurun üretilmesine neden olmuştur.

Gelecekte yapılacak çalışmalara öneri olarak, çamurun azaltımı yapan için aktif çamur sistemlerinin modifikasyonları, modelleme çalışmaları ile birlikte deneysel çalışmalarla desteklenebilir/geliştirilebilir.

1. INTRODUCTION

Activated sludge process is the most widely used treatment process for domestic wastewaters and also for a certain spectrum of industrial wastewaters. The process ends up with a treated effluent and a bulk amount of sewage sludge as a by-product. The treated effluent in compliance with the discharge criteria is discharged to a receiving body, whereas the sewage sludge needs to be further treated before final disposal.

During the early development of the activated sludge process, sludge generation was not considered as an important issue. Process alternatives were developed without full understanding of the problems observed. Plant improvements were mainly focused on sustaining an activated sludge with good settling properties; this would insure satisfactory system performance when coping with increasing sewage loads due to rapid population expansion and industrial development. Modifications mostly relied on experience and good judgment and implemented on a trial and error basis (Orhon, 2015).

Depending on the wastewater characteristics the produced sludge has a complex character composed of different substances. Reducing the sludge production is increasingly attractive as a result of rising costs and constraints with respect to sludge treatment and disposal.

Several technologies have been developed for the reduction of the excess sludge using physical, chemical and biological processes. Conventionally, generated excess sludge was processed *externally* before final disposal. Biological stabilization was adopted to reduce the amount of sludge under either aerobic of anaerobic conditions. Anaerobic digestion was often preferred in large plants for energy recovery. Both aerobic stabilization and digestion only provided partial sludge reduction, necessitating appropriate final disposal in compliance with imposed restrictions and regulations (Low and Chase; 1999).

Extended aeration has been the only early process modification intended to minimize sludge production by *internal* stabilization, i.e. additional stabilization volume in the aeration tank. Extended aeration avoided separate/post aerobic stabilization or anaerobic digestion by decreasing the organic fraction of the activated sludge maintained in the reactor. Internal stabilization provided not only oxidation of sewage organics but also autooxidation of the microbial community. This modification involved over-dimensioning of the plant and was only applicable to small communities (McCarty and Brodersen, 1962).

During the development phase, substrate loading was the only parameter to control and evaluate the activated sludge process. Initially it was expressed as volumetric loading, i.e. daily amount of substrate per unit reactor volume: later, it was improved to specific substrate loading rate calculated as the daily amount of substrate per unit amount of biomass in the reactor, also known as food to microorganism ratio, F/M. For a long period, F/M ratio was adopted and used as the major parameter for system design.

A major milestone in the understanding and the mechanistic interpretation of the activated sludge process was the introduction of the sludge age, SRT as the principal parameter for system design, together with related mass balance equations. The fundamental relationship derived from these equations, clearly indicated that F/M cannot be independently adjusted for an activated sludge system operated at a selected sludge age, because it varies as a function of the selected sludge age. Since, F, i.e. the daily amount of substrate is set by the treated wastewater, the sludge age defines M, i.e. the amount of biomass sustained in the reactor and determines the specific growth rate, μ_H of the active biomass. This way, the balance between microbial growth and endogenous decay is adjusted in such a way that the system can be operated at a positive net growth corresponding to the selected sludge age (McKinney, 1963).

This fundamental relationship gives the important clue that all process modification that would break this balance in favor of endogenous decay and/or provide an independent increase in the endogenous decay level are likely to achieve a reduction in excess sludge generation. Conceptually this reduction can take place in two different process alternatives: (i) systems with active biomass in the influent; (ii) systems equipped with a separate reactor with sludge re-aeration.

The first of these modifications has been developed and found application under the name of *Oxic-settling anaerobic (OSA)* process. Essentially, it consists of an aerobic biological reactor operated at a selected sludge age with an anaerobic unit that receives the excess sludge and recycles back to the influent stream after stabilization. While considerable research effort has been devoted to this novel process where sludge generation is significantly reduced, the microbial mechanism involved still remained unsolved. Surprisingly enough, the available literature on the subject has never envisaged the possible effect of active biomass recycle on enhanced endogenous decay and excess sludge minimization (Goel and Noguera, 2006).

Sludge re-aeration was originally defined as "*continued aeration of the biomass after its initial aeration in the activated sludge process"*. While its practice dates back to the early plants, re-aeration volume was mostly limited to less than 10% of the total aeration volume. *Contact stabilization* was a significant application of re-aeration with a totally different concept. It involved only a small volume fraction, *the contact tank,* for direct aeration of wastewater. After settling activated sludge was directed to the *stabilization tank* constituting the main, i.e. much larger aerated volume, prior to return to the contact basin (Jenkins and Orhon, 1972).

Both modifications with internal sludge stabilization are applied for minimizing the sludge where a side-stream reactor is placed on the sludge return to expose the sludge to starvation conditions under aerobic or anaerobic conditions resulting a reduced observed sludge yield.

In this context, the main objective of this study was to evaluate the merit of these two process modifications, with full benefit of the novel modeling tools, which relate relevant microbial mechanisms to system performance, under different operating conditions, over a wide range of sludge age levels and other important parameters. A crucially important part of the study has been to develop specific models fully describing microbial processes and related mass balance for activated sludge modifications involving influent active biomass and re-aeration systems.

2. LITERATURE REVIEW

2.1 Activated Sludge Systems

Wastewater treatment plant is basically a facility where mechanical, physical, chemical and biological mechanisms are interoperating to remove the pollution parameters from wastewater (Hreiz et al., 2015). The activated sludge system is now used on a regular basis for biological treatment of municipal and industrial wastewaters. Various groups of microorganisms (heterotrophs and autotrophs) work together in the activated sludge process to carry out the mechanisms for carbon and nutrient (nitrogen and phosphorus) removal (Orhon, 2015).

Historical Development

History of the activated sludge process has been dating back to early 1880s to the work of Dr. Angus Smith who had examined the aeration of wastewaters in tanks and oxidation of the organic matter. Aeration of wastewaters was investigated by a number of researchers but Ardern and Lockett (1914) found that sludge played a significant role in the results obtained by aeration. Exploration of the role of aeration and microbial activity in the sewage treatment in the early studies created the basis for the accidental discovery of the activated sludge process. During the operation of the process, many problems came out and this situation leads to develop empirical expressions with process modifications. Then, efforts towards understanding the fundamentals of the process that related to substrate removal mechanism, process kinetics and stoichiometry. Scientific studies had also conceptual development of novel technologies (Ardern and Lockett, 1914; Metcalf and Eddy, 2003; Orhon, 2015).

Basic Process Description

Activated sludge process conventionally is composed of three main compartments: (i) an aeration reactor in which the microorganisms responsible for treatment, (ii) a sedimentation tank in which liquid and solid separation occurs and (iii) a recycle line for returning separated solids from the sedimentation tank. Figure 2.1 shows the schematic diagram of the conventional activated sludge process (Metcalf and Eddy, 2003).

Conventional activated sludge (CAS) is modern configuration of early processes. The bioreactor is usually rectangular shaped with influent stream and return activated sludge exiting the opposite end. In the CAS process, hydraulic retention time (HRT) typically ranges between 4-8 hours, while sludge retention time (SRT) ranges between 3-8 days (Grady et al., 1998).

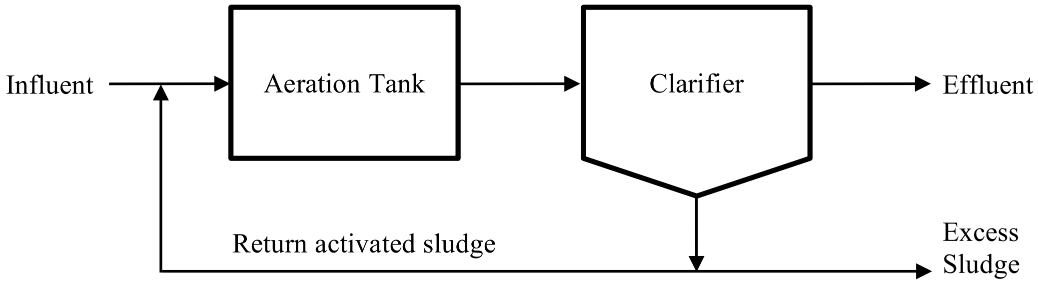

Figure 2.1 : Schematic diagram of the conventional activated sludge process (Metcalf and Eddy, 2003).

Microorganisms consume the colloidal matters and dissolved organics in the aerated bioreactor. Purpose of the aeration reactor is supply dissolved oxygen for the biodegradation. On the other side, activated sludge is gravitationally separated from the treated sewage in the clarifier (settling tank) and the effluent stream goes into the receiving environment. A sludge recycle line allows to return the settled sludge to the aeration tank to keep high bacteria concentration in the bioreactor while some portion of the sludge is detracting from sludge wastage line (Hreiz et al, 2015).

Essentially, all aerobic biological treatment processes can be operated on the basis of the same philosophy. They only differ in the conditions under which the biological reactions are restricted to operate. The activated sludge system is taken into account with following features such as flow regime in the reactor, the size/shape, number and configuration of the reactors, recycle stream, influent flow and other features. The essential kinetic response of an activated sludge process, for instance sludge production (sludge mass) and oxygen demand, is given by presuming that the system is completely mixed and the influent flow and load are constant. This presupposition allows determining the volume of reactor, mass of sludge wasted and oxygen utilization rate (OUR) by using simple mathematical expressions (Henze et al., 2008).

2.2 Modelling of Activated Sludge Systems

Modelling of activated sludge processes has become a common part of the design and operation of wastewater treatment plants. The Activated Sludge Process Model No.1 (Henze et al., 1987), known as ASM1, could be considered as a reference model developed to describe the removal of organic compounds. In 1995 ASM2, the Activated Sludge Process Model No.2 (Gujer et al., 1995) was published including biological nitrogen removal. The ASM2 model was expanded in 1999 into the ASM2d model, where biological phosphorus removal was considered and denitrifying PAOs were included. In 1998 ASM3 (Gujer et al., 1999) was developed to create a new tool to be used in the next generation of activated sludge models. The ASM3 was based on recent developments in the understanding of the activated sludge processes with the storage mechanism.

Using models will help to; (i) getting perception into plant performance, (ii) appraising different scenarios, (iii) evaluating plant design, (iv) criticizing of management decisions and (v) developing new control schemes.

Models provide a common language platform to the users when utilizing the concepts. It also has an organizing effect, helping researchers to achieve more efficient experimental designs and asisting operators to better understand and organizing the information to be used appropriately available at the wastewater treatment plants. A more important benefit of using the models is that they serve as guidance for research. Models are also providing possibility of saving time and money in terms of either process or technology selection (Henze et al., 2008).

Time and scale are two view points which are relevant in modelling approach. Basically, processes can be classified into three groups with regard to aspect of time: (i) dynamic state, (ii) frozen state and (iii) steady state. Models are generally made to depict the dynamic state where variations arise as a function of time. If a system is in a frozen state, it means process will change in time, but not in the time interval. On the other side, there are processes that they are in steady state condition. Steady state processes occur so fast, therefore rapid processes do not have to be identified in a dynamic way so that processes are proceeding so fast that can have assumed as in equilibrium condition. In activated sludge modelling, scaling is neglected because of not relevant enough to be taken into account (Henze et al., 2008).

Specific commercial simulation programs, AQUASIM, BIOWIN, GOLDSIM etc. are used for studying the effect of different environmental conditions, testing the system sensitivity to different parameters and applying different control configurations. Most of the simulation programs contain predefined process models offering the whole wastewater treatment plant. The selected process configuration can easily be constructed by connecting process units (Reichert, 1998; Url-1; Url-2).

2.3 Sludge Reduction Alternatives

One of the significant difficulties of biological wastewater treatment plants is high sludge generation. Treatment and disposal of excess sludge are the most challenging issues for wastewater treatment plants that are needed to handle owing to the economic, regulation and environmental aspects (Wei et al., 2003). Furthermore, the annual based generation of sewage sludge is expected to be increased gradually (Guo et al., 2013). The ratio of treatment and disposal cost of sewage sludge to total operation cost of the wastewater treatment plant is approximately between 50% and 60% (Davis and Hall, 1997; Spellman, 1997; Campos et al., 2009). Therefore, the decrease in the sludge formation is very important issue in terms of cost.

Several technologies have been proposed to reduce sludge generation within the activated sludge process rather than compete against sludge treatment and disposal (Niu et al., 2016). Therefore; there are remarkable applications to develop reducing excess sludge generation in biological wastewater treatment processes (Wei et al., 2003).

Conventional activated sludge process can be modified relying on different treatment plant configurations for producing less sludge in terms of mass. These modifications can be explained in two main approaches: *(i) in process treatment* to less sludge production by changing design or operational parameters and *(ii) post treatment* to reduce excess sludge for disposal (Mahmood and Elliot, 2006).

Improving the performance of the conventional activated sludge process is very vital in terms of operational, economical and environmental point of view. The number of in process sludge treatment methods was examined in the scope of this study.

2.4 In Process Applications

Conventional activated sludge treatment process is the most widely used as a wastewater treatment plants to deal with different types of sewage such as domestic and industrial wastewaters. In consequence of this treatment process, undesired excess sludge (waste activated sludge) by-product generated. Due to the generation of huge amount of excess sludge, the management and disposal of sewage sludge are very challenging issues. For this reason, a novel process that aims the reduction of sewage sludge during the operation potentially attracts the attention.

There are number of technologies that have been occurred to reduce excess sludge production from secondary treatment that utilize varieties of physical, chemical, biological and thermal processes. It is obtained that sludge reduction carries out on the basis of three mechanisms; (i) increasing the rate and extent of particulate matter degradation by solubilizing sludge solids (ii) increasing the extent of degradation by transforming a portion of the unbiodegradable components into biodegradable matter (iii) modifying the treatment process such as removing unbiodegradable components (Labelle et al., 2015).

Reducing the sludge generation in the treatment plant itself rather than the post treatment will be an optimal pathway to solve problems caused by excess sludge (Wei et al., 2003). Many studies have been conducted on in process sludge reduction (Li et al., 2014a; Li et al., 2014b; Divyalakshmi et al., 2015; Yang et al., 2016; Niu et al., 2016).

2.4.1 In process sludge stabilization

Sewage sludge stabilization method are intended to reducing pathogens or offensive odors and eliminating the potential putrefaction. The principal techniques that used for sludge stabilization are biological stabilization, chemical stabilization and thermal stabilization. Biological stabilization can be characterized into three subgroups: (i) aerobic digestion, (ii) anaerobic digestion and (iii) composting as it can be seen from Figure 2.2 (Metcalf and Eddy, 2003).

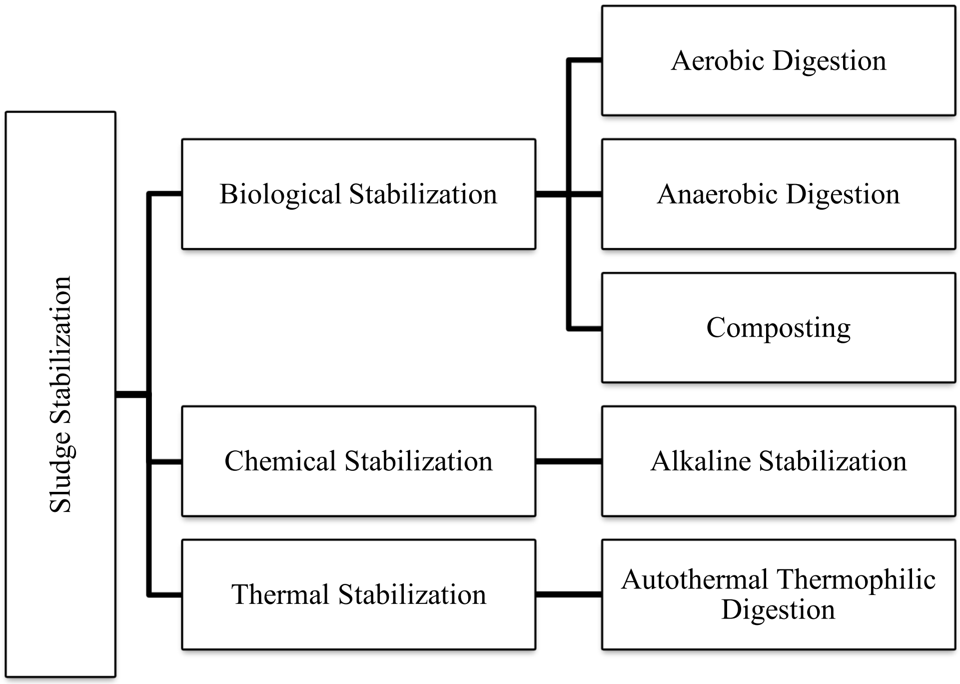

Figure 2.2 : Sludge stabilization methods.

Aerobic Sludge Stabilization

Aerobic stabilization is a process of decomposition of the organic proportion of the sludge by microorganisms in the oxygen environment. As a consequence of this process mass and volume of sludge reduce and stable product generated (Grady et al., 1998).

Microorganisms begin to deplete their protoplasm for cell maintenance when the soluble substrate is completely removed. Endogenous respiration is a fundamental process in aerobic stabilization on the basis of energy obtaining from cell material. The cell material is oxidized to carbon dioxide, water, and ammonia in aerobic environment (Tchobanoglous et al., 2003). Using typical formula of sewage sludge ($C_5H_7NO_2$) as representative of cell mass of a microorganism (Aasheim, 1985), the basic reaction of aerobic sludge stabilization (Reynolds, 1973) can be written by equation 2.1:

$$C_5H_7NO_2 + 7O_2 \rightarrow 5CO_2 + NO_3^- + 3H_2O + H^+ \qquad (2.1)$$

Aerobic stabilization can be implemented either as a separate process or as part of the biological treatment system.

Anaerobic Sludge Stabilization

Anaerobic digestion process involves the decomposition of organic matter in the absence of molecular oxygen and basically follows; hydrolysis, acidogenesis, acetogenesis, and methanogenesis mechanisms (Grady et al., 1998). The process can be used for industrial or domestic purposes to manage waste or to produce fuels.

Insoluble organic matter and high molecular weight materials for example lipids, polysaccharides, proteins and nucleic acids, degrades into soluble organic matter such as amino acids and fatty acids in the hydrolysis stage.

The second stage is acidogenesis stage where the substances that generated during hydrolysis are further split. Acidogenic bacteria produce volatile fatty acids (VFAs), coupled with carbon dioxide (CO_2), ammonia (NH_3) and other by products.

In the third stage, acetogenesis, organic acids (VFAs) and alcohols are converted to acetic acid together with carbon dioxide (CO_2) and hydrogen (H_2) by acetogenic bacteria.

The methanogenesis is final stage of anaerobic digestion. Two groups of methanogenic bacteria produce methane (CH_4). The first group of methanogenic bacteria separate acetate into methane and carbon dioxide, while the second group uses hydrogen (electron donor) and carbon dioxide (electron acceptor) to generate methane gas (Appels et al., 2008).

Methane gas (CH_4) is a beneficial end product of anaerobic digestion process due to high energy (35800 kJ/m^3) contain in itself. Methane gas can be also used as an energy source for heating the treatment units and/or generating electricity (Sanin et al., 2011).

Significant environmental parameters such as sludge retention time, temperature, pH, alkalinity and the presence of inhibitory substances effects the anaerobic digestion efficiency (Metcalf and Eddy, 2003).

Figure 2.3 shows the hydrolysis, acidogenesis, acetogenesis, and methanogenesis as four main stages of anaerobic digestion mechanism.

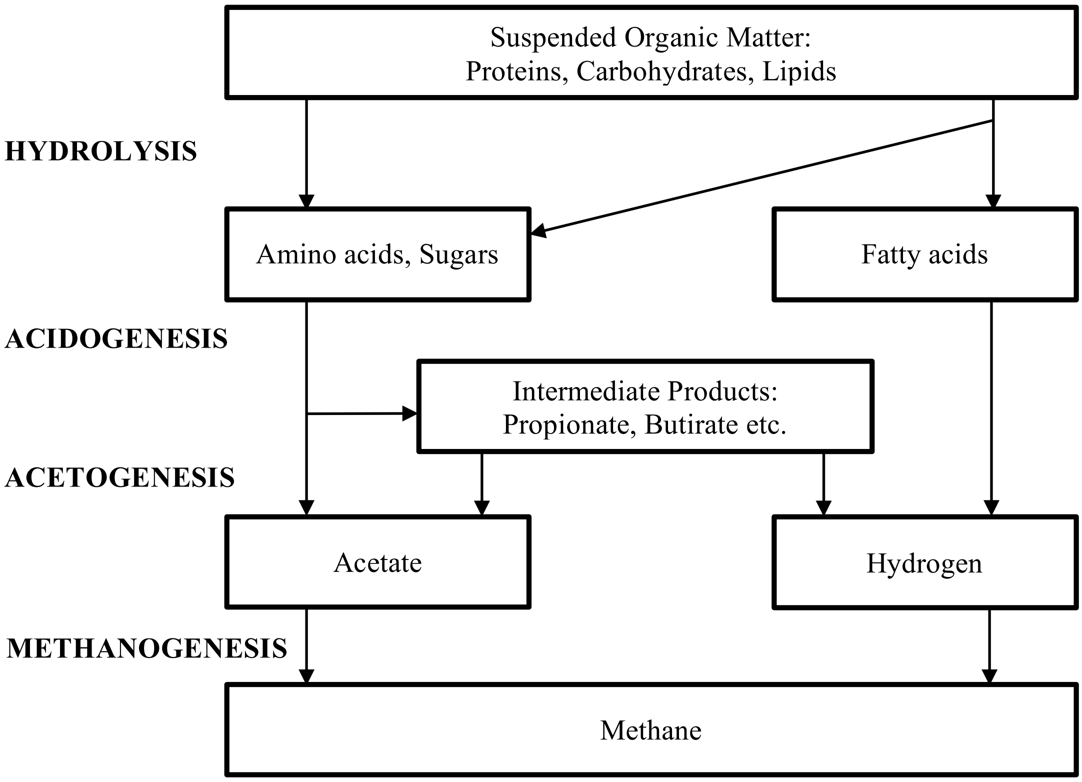

Figure 2.3 : Four main stages of anaerobic digestion mechanism.

Composting

Composting is a natural process where organic matter of sewage exposed to biological degradation to a stable end product and composted biosolids can be used as a soil conditioner in agricultural applications (WEF, 1995). Bacteria and fungi are responsible for the decomposition of major portion of the organic matter (Metcalf and Eddy, 2003).

Compost application happen in mesophilic, thermophilic, and cooling steps. Mesophilic step is the first stage where the temperature of the composting pile increases from ambient degree to 40°C. In the second step, thermophilic stage, temperature increases from 40°C to 70°C range. Finally, the microbial activity is reduced in the cooling step (Metcalf and Eddy, 2003; Turovskiy and Mathai, 2006).

Basic decomposing stages according to mesophilic, thermophilic, and cooling steps are (Metcalf and Eddy, 2003; Turovskiy and Mathai, 2006):

✓ *Pre-processing:* the mixing of sludge with a bulking agent such as wood chips, or leaves and yard waste.

- ✓ *High-rate decomposition:* aeration of composting pile by supplying air and/or by mechanical turning.
- ✓ *Storage/curing:* allows further stabilization and cooling of the composting pile.
- ✓ *Recovery of bulking agent*
- ✓ *Post-processing:* to remove non-biodegradable material for example metals, plastics etc.

Alkaline Stabilization

Alkaline stabilization application is basically a chemical stabilization that consists of addition of alkaline substances. The alkali material has to be maintained at the desired level for an adequate time in order to efficiently remove the pathogens (Amuda et al., 2008). Lime is usually added to sewage sludge for to raise pH over 12 to make conditions unfavorable for the growth of microorganisms. The stabilized sludge by using alkaline stabilization method, is appropriate for agricultural applications, landscaping etc. Alkaline stabilization technique is the most cost-effective process for sludge stabilization due to chemical substances such as lime or other alkaline materials are relatively expensive (EPA, 2000).

Autothermal thermophilic digestion

High-rate digesters usually run at 30 to 38°C range but autothermal thermophilic digestion occurs at 50 and 57°C temperatures that appropriate for thermophilic bacteria. Biochemical reaction rates increase due to the temperature. Therefore, thermophilic digestion is faster rather than mesophilic digestion. Volatile solids reduction and destruction of pathogenic organisms are increase during the thermophilic digestion. However, significant disadvantages of this process are higher energy requirements for heating, lower quality supernatant, odors, and less process stability (WEF, 1987).

2.4.2 In process sludge stabilization implementations

In process sludge stabilization applications was examined under three subtopics. These applications are extended aeration process, oxic-settling-anaerobic process and contact stabilization process.

In process treatment of sewage sludge applications has been studied throughout the history. It has been a prominent system among sludge re-aeration systems that is basically consists of aerating settled activate sludge in side-stream stabilization reactors (Orhon, 2014).

Extended Aeration Process

Extended aeration process was first carried out in 1947 with the purpose of amend an under loaded conventional activated sludge plant which was operated with 100% return sludge without sludge wasting in the US (McCarty and Brodersen, 1962).

Extended aeration process is a typical example among the modifications of the activated sludge system except that extended aeration process has low organic load and long hydraulic retention time (Orhon, 2015). Long hydraulic retention time that provided in the aeration tank is the distinguishing characteristic of the system. Not only, system contributes the aerobic digestion of the biomass in the aeration tank, but also it reduces the excess sludge volume for disposal. This system has been accrediting with the extended endogenous decay of biosolids in the reactor as an example of internal stabilization process (Özdemir et al., 2014). Apparently active biomass that is exposed endogenous decay, is only a fraction of the biomass sustained in the reactor (Henze et al., 1987; Orhon and Artan, 1994). Figure 2.4 illustrates the flowchart of the extended aeration process.

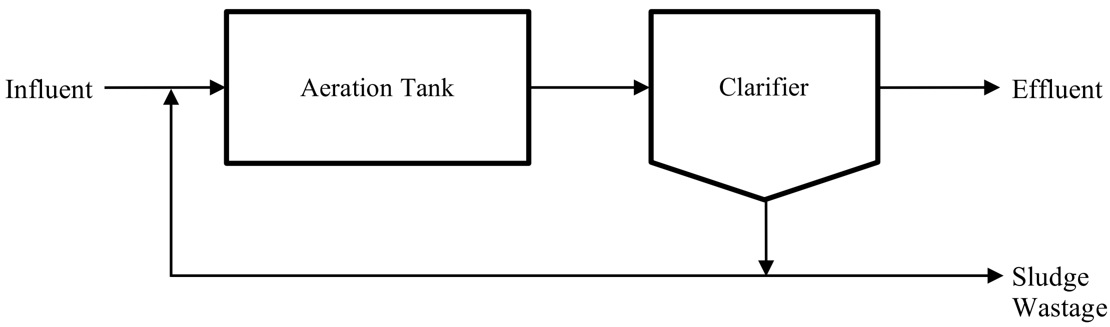

Figure 2.4 : Extended aeration process flowchart

Larger aeration tanks with longer sludge retention times that generally exceeding 20 days are used in the extended aeration process. Therefore, it is applicable to small communities because of the simplicity of the operation and relatively low cost (Metcalf and Eddy, 2003). Because of the large volume requirements and operational conditions, extended aeration process is excluded the modelling study.

Oxic-Settling-Anaerobic (OSA) Process

The oxic-settling-anaerobic (OSA) process has been established for the anaerobic stabilization zone in the return sludge line of conventional activated sludge process, as promising option for the sludge reduction.

The OSA process is commercialized as Cannibal Process that is one of the considerable process configurations for sludge minimization (Siemens Water Technologies Corporation, 2007).

OSA process is prominently preferred because of its several advantages among the other existing sludge reduction process configurations.

The key advantage of the OSA process is that it has shown the weighty sludge reduction without addition of any chemical substances or technologies (Yang et al., 2016). Other significant advantages can be listed such as being easily implemented in the part of existing CAS and bringing about sludge reduction into questions without effluent quality impairment (Demir and Filibeli, 2016).

Several researchers have investigated the possible sludge reduction mechanisms and they achieved significant sludge reduction efficiencies using either OSA or modified OSA systems compared to CAS system as it can be seen from Table 2.1. According to the related studies, sludge reduction ratios in terms of production were given in the range between 15% and 87% in comparison with CAS system. It is obvious that the decreasing sludge production ratios ranged between 15% and 58% in original OSA systems when compared to CAS.

Raw sewage is first feed into aerobic reactor and after aeration, wastewater goes to the settling tank. Supernatant of the sewage in the settling tank leaves the system. A portion of settled substances is return to aerobic reactor, while the remain part go to the anaerobic reactor. Digested sludge is feed into the inlet stream of the aerobic reactor after anaerobic digestion.

The schematic representation of the OSA process can be seen in Figure 2.5.

Table 2.1 : Sludge reduction efficiencies using OSA/modified OSA systems.

Reference	Wastewater	Process Configuration	Reduced Sludge Production
Saby et al., 2003	Synthetic wastewater	Modified oxic-settling-anaerobic process with membrane bioreactor	23%-58%
Ye and Li, 2010	Synthetic wastewater	Oxic-settling-anaerobic process combined with 3,3’,4’,5-tetrachlorosalicylanilide (TCS)	21%-56%
Li et al, 2014c	Synthetic wastewater	Modified oxic-settling-anaerobic process with a sludge holding tank	30%-60%
Ning et al., 2014	Synthetic wastewater	Anoxic-oxic-settling-anaerobic process (A-OSA)	49%
Sun et al., 2015	Synthetic wastewater	UNITANK-oxic-settling-anaerobic process	48%
Khursheed et al., 2015	Synthetic wastewater	Oxic-settling-anaerobic process	15%-40%
Yagci et al., 2015	Synthetic wastewater	Oxic-settling-anoxic process with iron dosing	38%-87%
Zhou et al., 2015a	Dongqu WWTP (Shangai, China)	Anoxic-oxic-settling-anaerobic process (A-OSA) revealed by 454-pyrosequencing	30.4%
Zhou et al., 2015b	Dongqu WWTP (Shangai, China)	Anoxic-oxic-settling-anaerobic process (A-OSA)	32%
Demir and Filibeli, 2016	Synthetic wastewater	Oxic-settling-anaerobic process	58%
Rodriguez-Perez and Fermoso, 2016	Municipal WWTP in Seville (Spain)	Oxic-settling-anoxic process	53%

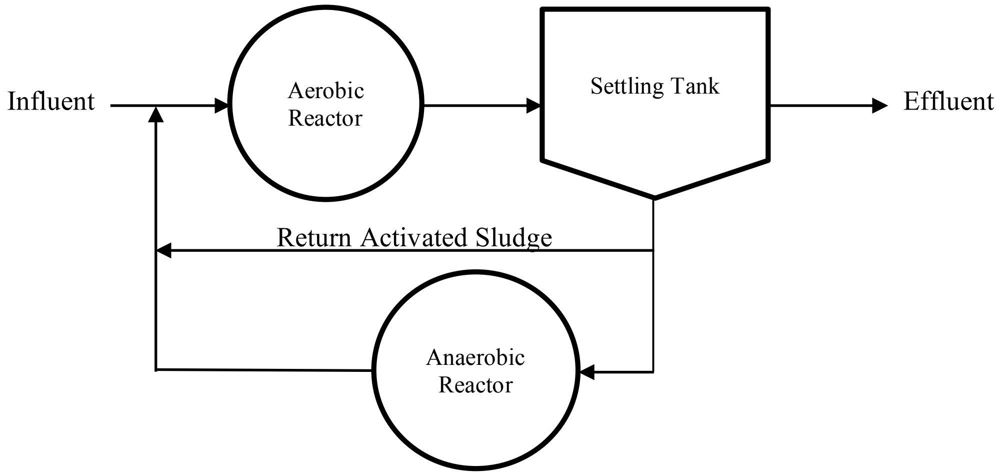

Figure 2.5 : A schematic diagram of the OSA process.

Contact Stabilization Process

Contact stabilization process consist of two aerated reactors: Contact reactor (CR) and stabilization reactor (SR). Sewage and activated sludge aerated for 0.5-1.5 hours in the contact tank. On the other hand, sludge that separated in settling tank is re-aerated for 1.5-8 hours in the stabilization tank. Then, re-aerated sludge returns into contact tank. Volumetric loading capacity increases by using contact stabilization process in place of conventional activated sludge process (Jenkins and Orhon, 1972). One of the main advantages of the contact stabilization process is short hydraulic retention time in the contact reactor that allows the decrease treatment volume (Sarria et al., 2011).

The basic design and operational parameters of activated sludge system are hydraulic retention time, sludge retention time, sludge recycle rate, volumetric organic load, food-microorganism ratio, sludge settling properties (such as sludge volume index, SVI), dissolved oxygen (DO) concentration and mixed liquor volatile suspended solids (MLVSS) (Grady et al.,1998; Sarria et al., 2011).

The MLVSS concentration represents the biomass in the system. Generally, MLVSS values for activated sludge systems change between 500-5000 mg/L. For the contact stabilization process; 1000-3000 mg MLVSS/L and 4000-10000 mg MLVSS/L are recommended for contact and stabilization tank, respectively (Sarria et al., 2011).

A schematic representation of the contact stabilization process is given in Figure 2.6 A portion of sludge mass removes the carbonaceous materials from the influent in the contact tank. A small fraction of the adsorbed organic substrate is metabolized in contact reactor and accordingly, sludge mass consists high proportion of unmetabolized COD. Excess sludge is wasted from the system (Alexander et al., 1980).

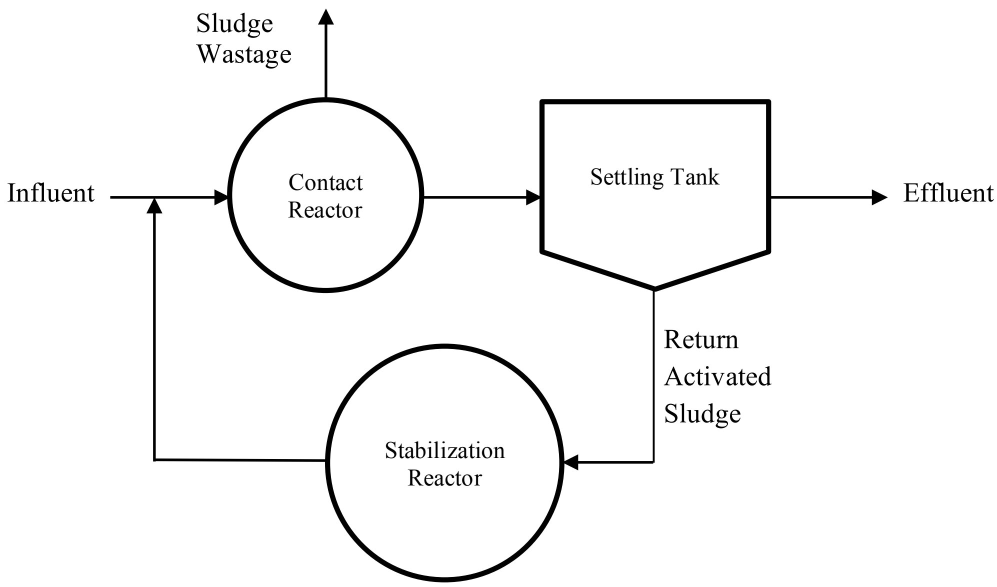

Figure 2.6 : A schematic diagram of the contact stabilization process.

3. MATERIALS AND METHODS

3.1 Structure of the Adapted Model and Simulation Software

Model structure

The model used in this study is a modified version of Activated Sludge Model No. 1, ASM1 (Henze et al., 1987) as suggested by Orhon and Artan (1994). The modified model differs from the the original ASM1 with the addition of endogenous decay process and dual hydrolysis step. The model components account for all COD fractions together with the active heterotrophic biomass and dissolved oxygen.

The model consists of four main components: (i) COD fractions: readily biodegradable COD (S_S), readily hydrolyzable COD (S_H), slowly hydrolyzable COD (X_S), soluble inet COD (S_I), particulate inert COD (X_I); (ii) residual microbial products generated by endogenous decay processes: soluble residual microbial products (S_P), particulate residual microbial products (X_P); (iii) active heterotrophic biomass (X_H) and (iv) dissolved oxygen (S_O).

The model has also four biochemical processes: (i) growth of active heterotrophic biomass (X_H) on readily biodegradable substrate (S_S); (ii) hydrolysis of readily hydrolyzable substrate (S_H) to readily biodegradable substrate (S_S); (iii) hydrolysis of slowly hydrolyzable substrate (X_S) to readily hydrolyzable substrate (S_S) and (iv) decay of active heterotrophic biomass (X_H).

The components and processes are represented in a matrix format as given in Table 3.1 depending on the process scheme described in Figure 3.1.

The first five components represent the total COD measured. The inert fractions (soluble inert (S_I) and particulate inert (X_I)) do not go through a biochemical reaction. S_I, passes through the activated sludge system, while X_I retains and only removed by sludge wastage. The biodegradable part of the COD is mainly accounted for readily and slowly biodegradable COD based on their biodegradability. Readily biodegradable fraction may be comprised of simple carbohydrates, volatile fatty acids (VFAs), alcohols etc. Heterotrophic growth takes place on readily biodegradable substrate as a function of Monod-type expression. Slowly biodegradable fraction consists of soluble, colloidal, larger complex organic matter which can not pass through the cell wall. Slowly biodegradable substrate must first be converted into simpler organics for the utilization. This mechanism is called hydrolysis which is slower than the utilization of readily biodegradable COD. Hydrolysis rates are expressed in terms of saturation-type surface reaction kinetics.

The model structure highlights the major role of the dissolved oxygen concentration (S_O) as a direct parameter taking part in the switch functions of process rates.

The generation of the residual microbial products S_P and X_P are formulated as a decay associated process. Their existence in the model lead to a better interpretation of oxygen demand.

Endogenous decay is defined by a first degree reaction with respect to X_H.

The model was used for evaluating organic carbon removal in OSA and CS systems.

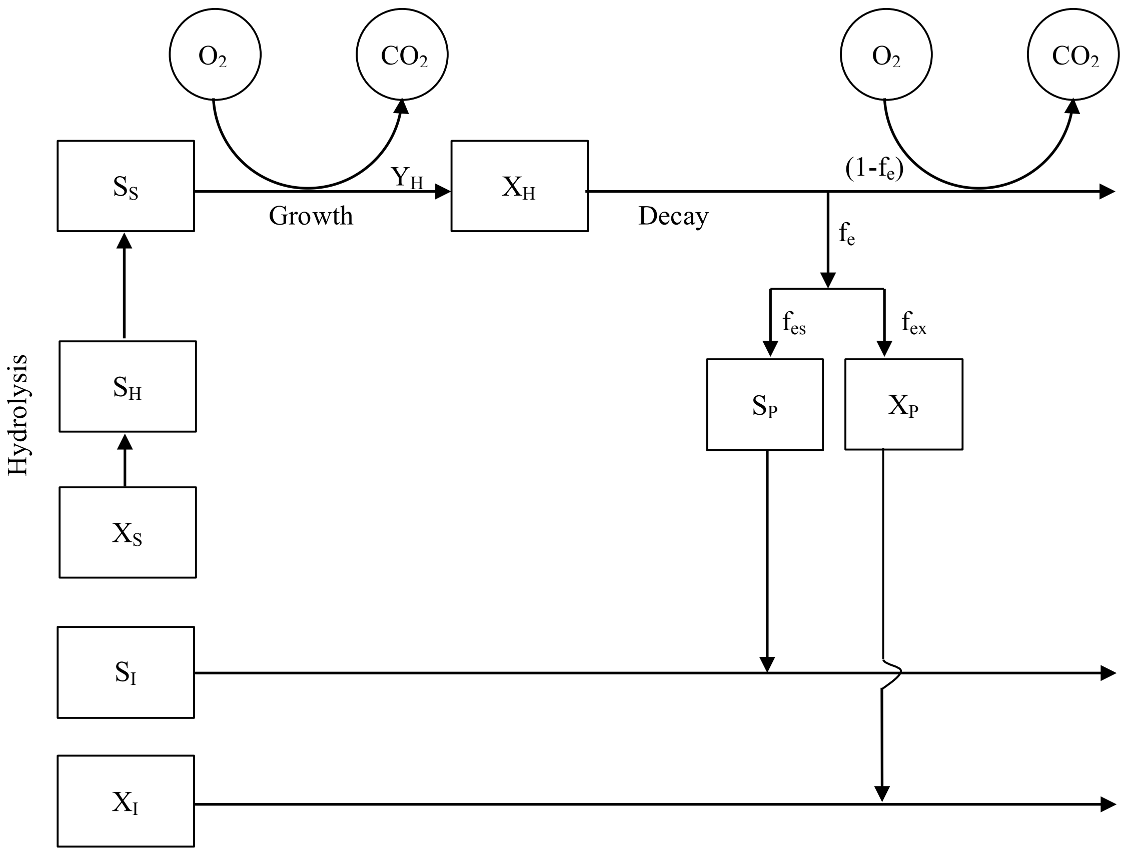

Figure 3.1 : Process scheme for endogenous decay model (Orhon and Artan, 1994).

Table 3.1 : Matrix representation of the modified ASM1 model (Orhon and Artan, 1994).

Components→ Processes↓	S_I	X_I	S_S	S_H	X_S	S_O	X_P	S_P	X_H	Rate Equations
Growth of X_H			$-\frac{1}{Y_H}$			$-\frac{1-Y_H}{Y_H}$			1	$\hat{\mu}_H\left(\frac{S_S}{K_S+S_S}\right)\left(\frac{S_O}{K_{OH}+S_O}\right)X_H$
Hydrolysis of S_H			1	-1						$k_{hs}\left(\frac{S_H/X_H}{K_{XS}+\left(S_H/X_H\right)}\right)\left(\frac{S_O}{K_{OH}+S_O}\right)X_H$
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						$-(1-f_{ex}-f_{es})$	f_{ex}	f_{es}	-1	$b_HX_H\left(\frac{S_O}{K_{OH}+S_O}\right)$
Parameters	COD	COD	COD	COD	COD	O_2	COD	COD	cell COD	

Figure 3.2 shows the conjugate dependencies between the four subsystems of the simulation program: (i) variables, (ii) processes, (iii) compartments and (iv) links. The written differential equations for water flow and substance transport can be selected by the choice of environmental or technical compartments. Compartments may be connected by using links. Equations describes the effect of alternation of the process and the source terms of these equations can be freely specified by the user. The description of processes, compartments and links can be done by means of variables that reflect objects taking a context-sensitive numerical value. It is apparent that the variables form the basic subsystem required for the formulation of processes, compartments and links. Lastly, links can be used to connect compartments. All definitions are together formed in the AQUASIM for simulation and data analysis (Reichert, 1998).

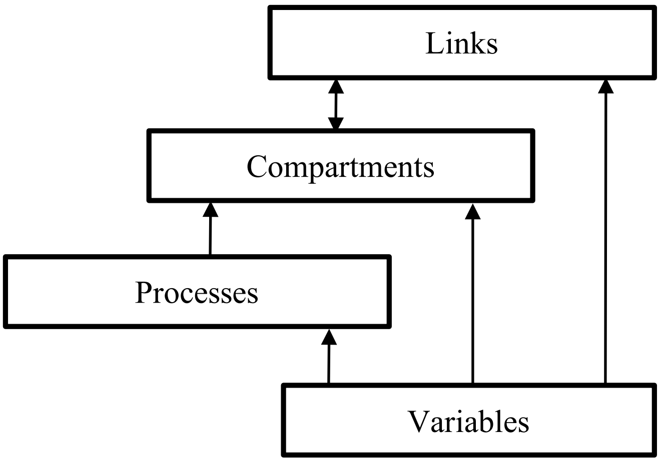

Figure 3.2 : Main elements of model structure (Reichert, 1998).

The program allows the users to define the WWTP configuration to be investigated as a set of compartments, which can be connected by using links. The matrix representation of the modified ASM1 model was concerted to the AQUASIM sofware to simulate the OSA and CS processes.

Completely stirred reactor (CSTR) was selected for the modelling. Inflow, outflow and transformation processes of substances were defined in the CSTR compartment with constant volume. Predefined processes were activated in the CSTR. Execution of a simulation is equivalent to numerically integrating a system of ordinary and partial differential equations in time and simultaneously solving the algebraic equations (Reichert, 1998). AQUASIM interface can be seen in Figure 3.3.

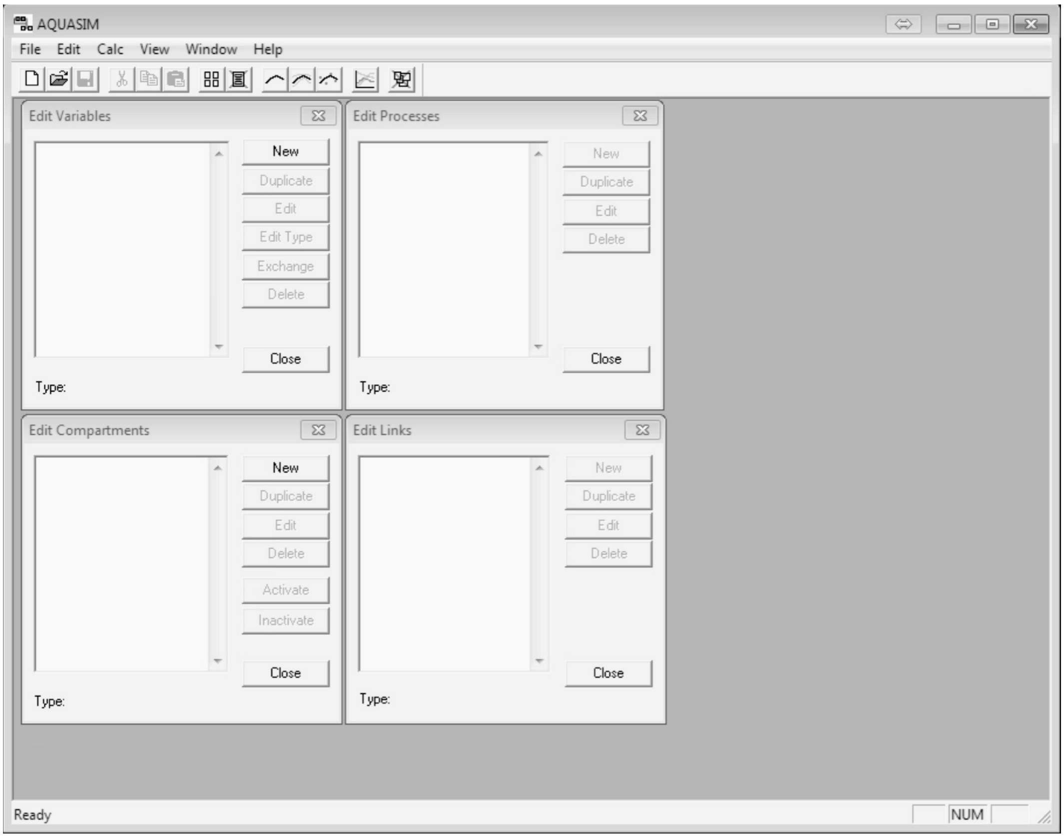

Figure 3.3 : AQUASIM interface.

3.2 Wastewater Characteristics

The model was run considering the characteristics of domestic wastewater originated from Istanbul, Kadıköy (Orhon et al, 1997). Conventional characterization indicated that the wastewater had a moderate strength with a total COD of 500 mg/L consisted of approximately 35% soluble and 65% particulate portions. The detailed biodegradability oriented characterization outlined that the inert organic matter was 75 mg/L, divided as 25 mg/L in soluble part and 50 mg/L in particulate part.

The readily biodegradable COD of the same wastewater was estimated with respirometric tests. It was calculated to be around 10% of the total COD, with a value of 50 mg/L using the oxygen uptake profiles. These profiles also indicated a rapidly hyrolyzable COD of 100 mg/L and slowly biodegradable COD of 275 mg/L. The COD fractions and their percent distribution are outlined in Table 3.2 (Orhon et al, 1997).

Table 3.2 : Wastewater characterization used for modelling (Orhon et al., 1997).

Parameter		Concentration (mg/L)	Fraction in total (%)
Conventional Characterization			
Total COD	C_{T1}	500	100
Total soluble COD	S_{T1}	175	35
Total particulate COD	X_{T1}	325	65
Treatability Oriented Characterization			
Readily biodegradable COD	S_{S1}	50	10
Rapidly hyrolyzable COD	S_{H1}	100	20
Slowly biodegradable COD	X_{S1}	275	55
Soluble inert COD	S_{I1}	25	5
Particulate inert COD	X_{I1}	50	10

3.3 Stoichiometric and Kinetic Coefficients

The stoichiometric and kinetic coefficients were directly used in the modelling obtained for the same wastewater (Orhon et al., 2002).

The comparison of both domestic wastewaters in terms of the stoichiometric and kinetic coefficients revealed that the characteristics indicating slightly higher hydrolysis rates, but significantly lower maximum growth rates for Ataköy wastewaters (Tas et al, 2009).

Table 3.3 summarizes the selected stoichiometric coefficients and kinetic coefficients for modelling adapted from Orhon et al. (2002).

Table 3.3 : Kinetic and stoichiometric coefficients used for modeling (Orhon et al., 2002).

Model Parameter		Unit	Value
Yield coefficient of X_H	Y_H	g cell COD/g COD	0.64
Maximum heterotrophic growth rate	$\hat{\mu}_H$	1/day	5.00
Half saturation constant for growth	K_S	mg COD/L	5.00
Endogenous decay rate	b_H	1/day	0.20
Half saturation coefficient for oxygen	K_{OH}	mg O_2/L	0.01
Maximum hydrolysis rate for S_H	k_{hs}	1/day	3.50
Hydrolysis half saturation constant for S_H	K_{XS}	g COD/g COD	0.01
Maximum hydrolysis rate for X_S	k_{hx}	1/day	1.00
Hydrolysis half saturation constant for X_S	K_{XX}	g COD/g COD	0.04
Fraction of biomass converted to S_P	f_{es}	-	0.05
Fraction of biomass converted to X_P	f_{ex}	-	0.15

3.4 Modelling Approach

Activated sludge systems with three different configurations were modelled in terms of different operational parameters. Each system was run with the same wastewater characteristics, stoichiometric and kinetic parameters and the same flowrate of 10000 m^3/d using the process rates defined in the previous subsection.

Conventional Activated Sludge Process

Conventional activated sludge system, CAS, was used as a control system for comparing and evaluating the sludge production in the other configurations. CAS modelling was executed at sludge ages 6, 8, 10, 12 and 15 days with the framework given in Table 3.4. The volume of the aeration reactor was set to 3350 m^3 and 2100 m^3 so that a hydraulic retention time of 8 and 5 hours was achieved.

Table 3.4 : Framework of CAS process.

		Volume (m^3)	HRT (d)	Active Processes
Run 1	Reactor	V 3350	HRT 0.335	*growth and decay of X_H,* *hydrolysis of S_H and X_S*
	Settling	V_{set} 2000	HRT_{set} 0.2	-
Run 2	Reactor	V 2100	HRT 0.21	*growth and decay of X_H,* *hydrolysis of S_H and X_S*
	Settling	V_{set} 2000	HRT_{set} 0.2	-

Excess sludge wastage was performed from the aerobic reactor. The wastage flow rate (Q_W) and return activate sludge flow rate (Q_R) were adjusted to maintain the desired SRT.

Oxic-Settling-Anaerobic Process

OSA process was practiced in the modelling study by considering a simplified approach where the initial biomass content in the wastewater acted as the outflow of the anaerobic reactor located in the sludge recirculation line. The system was converted to an easier configuration by omitting the anaerobic stabilization reactor and introducing an initial biomass directly to the aeration tank. The basic assumption relied on the fact that excess sludge has been stabilized elsewhere and returned to the system as a viable heterotrophic active biomass. The system was transferred to a conventional system receiving an active biomass with the wastewater flow.

OSA system was modelled with different initial active biomass concentrations (X_{H1}) in a range of 50 to 200 gr cell COD/m^3 under the conditions defined in Table 3.5. The range for active biomass was determined by assuming a fraction for heterotrophic active biomass with the ability to switch on to aerobic conditions.

The volume of the main reactor was selected as 3350 m^3, so that the HRT was adjusted to 0.335 d. *Growth of X_H, hydrolysis of S_H, hydrolysis of X_S and decay of X_H*

processes were activated in the aeration reactor. Settling tank has 2000 m^3 volume and none of the biological process was activated in this tank.

Excess sludge wastage was performed from the aerobic reactor. The wastage flow rate (Q_W) and return activate sludge flow rate (Q_R) were adjusted to maintain the desired SRT.

Table 3.5 : Framework of OSA process.

	Volume (m^3)	HRT (d)	Active Processes
Reactor	V	HRT	*growth and decay of X_H,*
	3350	0.335	*hydrolysis of S_H and X_S*
Settling	V_{set}	HRT_{set}	-
	2000	0.2	

Contact Stabilization

CS process consists of three reactors: an aerobic contact reactor, a settling reactor and an aerobic stabilization reactor located in the recirculation stream.

Two runs with two different HRTs were executed. In the first run total HRT was selected as 8 hours divided into CR and SR in a ratio of 1/10. The volumes of the CR and SR were selected 300 m^3 and 3000 m^3, respectively, to adjust the HRT as 0.03 d in CR and 0.3 d in SR. Second run was conducted for a total HRT of 5 hours divided again 1 to 10 in both reactors, the volumes were selected 200 m^3 and 1900 m^3 for CR and SR, respectively, to achieve an HRT of 0.02 d in CR and 0.19 d in SR.

Due to the short HRT, it was expected that only soluble substrate could be removed in the contact reactor and endogenous respiration would be negligible if compared to growth process. The removal of particulate substances was directed to SR operated at a sufficient solid retention time together with a sufficient and hydraulic retention time. Regarding the modeling aspects only *growth of X_H* and *hydrolysis of S_H* processes were activated in the CR (*endogenous decay* and *hydrolysis of X_S* were inactivated). On the contrary, all processes (*growth of X_H, hydrolysis of S_H, hydrolysis of X_S and decay of X_H*) were initiated in the stabilization reactor (Table 3.6). In the settling tank with a volume of 2000 m^3 it was accepted that no biological reaction took place.

Table 3.6 : Framework of CS process.

		Volume (m^3)	HRT (d)	Active Processes
Run 1	Contact Reactor	V_C	HRT_C	*growth of X_H,*
		300	0.03	*hydrolysis of S_H*
	Stabilization Reactor	V_S	HRT_S	*growth and decay of X_H,*
		3000	0.30	*hydrolysis of S_H and X_S*
	Settling	V_{set}	HRT_{set}	-
		2000	0.2	
Run 2	Contact Reactor	V_C	HRT_C	*growth of X_H,*
		200	0.02	*hydrolysis of S_H*
	Stabilization Reactor	V_S	HRT_S	*growth and decay of X_H,*
		1900	0.19	*hydrolysis of S_H and X_S*
	Settling	V_{set}	HRT_{set}	-
		2000	0.2	

Excess sludge wastage was performed from the contact reactor. The wastage flow rate (Q_W) and return activate sludge flow rate (Q_R) were adjusted to maintain the desired SRT.

4. RESULTS

Three different activated sludge configurations, CAS, OSA and CS, were evaluated in terms of sludge production by conducting a modeling study using AQUASIM software (Reichert et al., 1998) for carbon removal. Mass balances were written for each system and usually established around the inlet and outlet. The characteristics of the wastewater and the process kinetics used in the modeling were defined in the previous section.

The CAS, OSA and CS systems were scrutinized under different operational conditions to identify the effect of system configuration on the production of excess sludge. CAS was considered as a control system to predict the improvement in excess sludge production.

4.1 Conventional Activated Sludge System

Process Scheme

Conventional activated sludge system (CAS system) consists of an aeration reactor followed by a settling tank as it can be seen from Figure 4.1.

The wastewater is aerated in the aeration reactor for a sufficient period and the flocculent activated sludge is separated from the wastewater in the settling tank. The wastewater was assumed not to include any active heterotrophic biomass.

The treated wastewater flows (effluent stream of the wastewater treatment plant) forward for discharge. A portion of the settling tank underflow sludge is returned to the aeration reactor for mixing with the influent wastewater to the reactor and the remaining sludge that called as excess sludge is wasted to the sludge treatment facility.

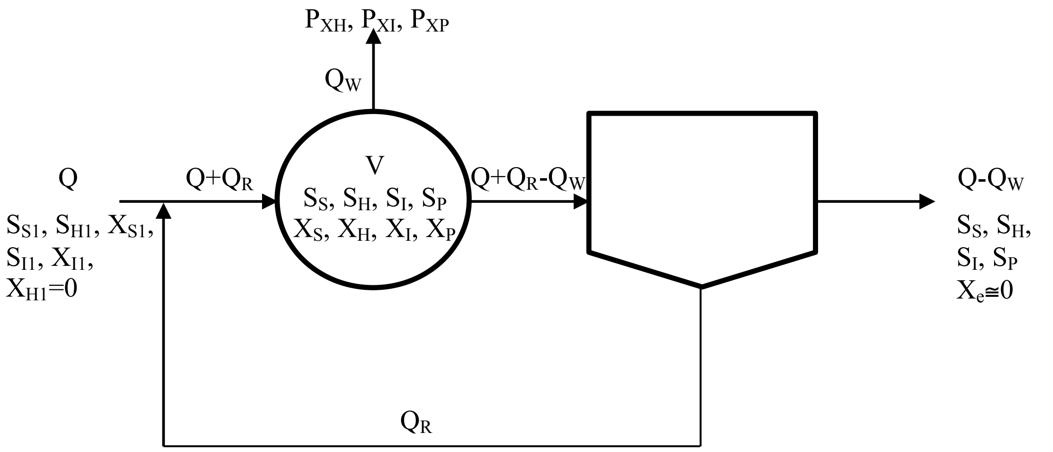

Figure 4.1 : Schematic diagram of the CAS process.

In a conventional activated sludge system, the amount of active heterotrophic biomass generated is directly depending on the biodegradable substrate utilized and the sludge age of the system. The mass balance for biodegradable substrate directs to the amount of biomass in the system.

$$Q\,C_{S1} - (Q - Q_W)C_S - q\,V\,X_H = 0 \tag{4.1}$$

In the equation (4.1): Q is influent flow rate (m^3/d); C_{S1} is total influent biodegradable substrate, ($S_{S1}+S_{H1}+X_{S1}$), (gr COD/m^3); C_S is total effluent biodegradable substrate, ($S_S+S_H+X_S$), (gr COD/m^3); V is volume of aerobic reactor (m^3); q is the amount of substrate removed per unit amount of active biomass per day (gr COD/gr cell COD.day) and X_H is active heterotrophic biomass in the reactor (gr cell COD/m^3).

Based on the process kinetics,

$$q = \frac{\mu_H}{Y_H} \tag{4.2}$$

and based on the assumption that all biodegradable substrate is used,

$$q = \frac{\mu_H}{Y_H} = \frac{Q\,C_{S1}}{V\,X_H} \tag{4.3}$$

This expression may be rearranged to define the amount of active biomass M_{XH} directly related to available substrate, ($Q\,C_{S1}$), and growth rate of the system (μ_H):

$$M_{XH} = V\,X_H = \frac{Y_H}{\mu_H}\,Q\,C_{S1} \tag{4.4}$$

By using the definition of net growth rate depending on the sludge age, SRT:

$$(\mu_H - b_H) = \frac{1}{SRT} \tag{4.5}$$

Inserting μ_H from equation (4.5) in equation (4.4) yields the active biomass in the reactor:

$$X_H = \frac{Y_H}{1+b_H\,SRT}\,C_{S1}\,\frac{SRT}{HRT} \tag{4.6}$$

With the assumption that the wastewater does not contain any active biomass (X_{H0}=0), the mass balance for active heterotrophic biomass in the CAS process:

$$-Q_W X_H + V\,X_H\,(\mu_H - b_H) = 0 \tag{4.7}$$

This expression is rearranged with the fact that the daily amount of total excess sludge needs to be wasted to maintain the system at steady state;

$$P_{XH} = Q_W X_H \tag{4.8}$$

$$P_{XH} = \mu_H\,V\,X_H - b_H V\,X_H \tag{4.9}$$

Using the equation (4.3) and (4.9), P_{XH} becomes;

$$P_{XH} = Y_H\,Q\,C_{S1} - b_H V\,X_H \tag{4.10}$$

Equation (4.10) clearly indicates that the sludge produced is the net balance between the growth and endogenous levels.

So, the net active biomass generation, P_{XHN}, can be obtained combining equations (4.6) and (4.10):

$$P_{XHN} = Y_H\,Q\,C_{S1} - Q\frac{Y_H}{1+b_H\,SRT}\,C_{S1}\,b_H\,SRT \tag{4.11}$$

From a net yield of view, Y_{NH}, biomass generation, P_{XH}, can be defined as:

$$P_{XH} = Y_{NH}\,Q\,C_{S1} \tag{4.12}$$

where,

$$Y_{NH} = \frac{Y_H}{1+b_H\,SRT} \tag{4.13}$$

As can be followed by the expressions, the mass of sludge ($V\,X_H$) is defined as a function of the available substrate concentration ($Q\,C_{S1}$) depending on the substrate removal rate (q) or specific growth rate of heterotrophs (μ_H) as a function of SRT. If ones the SRT is selected, the system keeps a certain amount of sludge ($V\,X_H$) and determines the amount sludge generated (P_{XH}). Equations (4.9) and (4.10) indicate that the available substrate plays an important role on the net sludge production, and the decrease in sludge production is only possible if the endogenous decay level is increased with the increase of the sludge age. The sludge production cannot be estimated as negative depending on the fact that the growth term is always greater than the decay term. It should be noted that increasing the sludge age also increases the volume of the system to an unfeasible level. This fundamental analysis leads to the survey of new treatment schemes with different configurations where endogenous decay process dominates the growth process.

Considering the other sludge fractions, the mass balance for particulate inert microbial product (X_P) generated can be described as:

$$-Q_W X_P + V\, f_{ex}\, b_H\, X_H = 0 \tag{4.14}$$

$$P_{XP} = f_{EX}\, b_H\, P_{XH}\, SRT \tag{4.15}$$

$$P_{XP} = \frac{V\, X_P}{SRT} \tag{4.16}$$

The value of X_P can be computed by using the value of P_{XP} in equation (4.16);

$$X_P = f_{ex}\, b_H\, X_H\, SRT \tag{4.17}$$

A corresponding mass balance can also have written for inert particulate COD of influent origin (X_I):

$$Q\, X_{I1} - P_{XI} = 0 \tag{4.18}$$

The daily rate of influent inert particulate COD wastage is expressed as a function of SRT,

$$P_{XI} = \frac{V\, X_{I1}}{SRT} \tag{4.19}$$

And the concentration of the influent inert particulate COD can be derived as:

$$X_I = \frac{X_{I1}\, SRT}{HRT} \tag{4.20}$$

Finally, the total biomass in the reactor, M_{XT} is calculated by considering all particulate components;

$$M_{XT} = M_{XH} + M_{XP} + M_{XI} \tag{4.21}$$

The value of M_{XT} is obtained by combining equations (4.12), (4.15) and (4.19);

$$M_{XT} = Q\, [Y_{NH} C_{S1}(1 + f_{ex} b_H SRT) + X_{I1}]SRT \tag{4.22}$$

The total biomass concentration can be calculated as;

$$X_T = X_H + X_P + X_I \tag{4.23}$$

$$X_T = [Y_{NH} C_{S1}(1 + f_{ex} b_H SRT) + X_{I1}] \frac{SRT}{HRT} \tag{4.24}$$

The total daily excess sludge production P_{XT} may then be calculated as a sum of each particulate compound generated in the system:

$$P_{XT} = P_{XH} + P_{XP} + P_{XI} \tag{4.25}$$

P_{XT} may also be defined introducing an overall sludge yield coefficient, Y_{NH}:

$$P_{XT} = Y_{NH}\, Q\, C_{S1} \tag{4.26}$$

Y_{NH} is a useful design parameter defining the amount of sludge produced per unit amount of biodegradable substrate utilized. This expression is derived with the assumption that all biodegradable substrate is consumed.

$$Y_{NH} = \frac{P_{XT}}{Q\, C_{S1}} \tag{4.27}$$

This expression indicates that total excess sludge P_{XT} varies as a function of the sludge age and the particulate inert COD fraction in the wastewater.

The recycle ratio, R, is a significant parameter that should be set accurately for the operation of the system.

It is expressed as;

$$R = \frac{Q_R}{Q} \tag{4.28}$$

where Q_R is the flow rate of biomass recycled (m^3/d).

The mass balance for total biomass created around the settling tank indicates the magnitude of R. This equation is written as if the sludge wastage is from the bottom of the settling tank.

$$(Q + Q_R)X_T - Q_R X_{RT} = P_{XT} \tag{4.29}$$

In the equation (4.29); X_T is suspended solids concentration in the reactor; X_{RT} is suspended solids concentration in the recycle flow and Q_W is flowrate of wastage, if wasted from the settling tank (m^3/d).

R is defined by dividing both sides of the equation (4.29) by ($V\, X_T$) and rearranging;

$$R = \frac{1 - \frac{\theta_h}{\theta_x}}{\frac{X_{RT}}{X_T} - 1} \tag{4.30}$$

R is the main operating parameter for adjusting the biomass balance between the aeration reactor and settling tank in activated sludge systems. In activated sludge systems operated with sufficient settling properties in relation to sludge volume index, X_{TR} becomes 2.5-3 times higher than the total biomass concentration in the reactor (X_T).

The wastage point does not have any effect in the operation, only the flow rate of the wasted sludge (Q_W) differs if it is wasted from the aeration tank as in this case. So the flow rate can be calculated as;

$$Q_W = \frac{P_{XT}}{X_T} \tag{4.31}$$

Results

The modeling results of CAS system illustrated the basic features of classical activated sludge system behavior. The variables that related to sludge properties in the reactor were calculated at different SRT values. The model was first run for an HRT of 8 hours to characterize the common operational conditions of a CAS. Then HRT was reduced to 5 hours to demonstrate the limitation of system operation due to the settling conditions.

For the HRT of 8 hours the volume of the reactor was selected as 3350 m^3. The simulations were conducted with the assumption that the solid from the aeration tank was thickened 3-fold more in the settling tank, so that the solid concentration in the recycled flow (X_R) is 3-fold of the solid concentration in the aeration tank (X_T).

The simulations at steady state conditions indicated that the soluble biodegradable substrate consisting of 50 mg COD/L S_S and 100 mg COD/L S_H were fully utilized in the CAS system at any sludge age selected. The only difference in the effluent was the amount of soluble microbial product generated (S_P) in the biological activities. The initial inert soluble substrate S_I, remained the same at different sludge ages, since it did not go in any biological reaction.

Figure 4.2 shows the total soluble matter concentration, S_T, with a very minor increase from 34 to 36 gr COD/m^3 with the increase of sludge age from 6 to 15 d. This values majorly reflected the sum of the S_I and S_P.

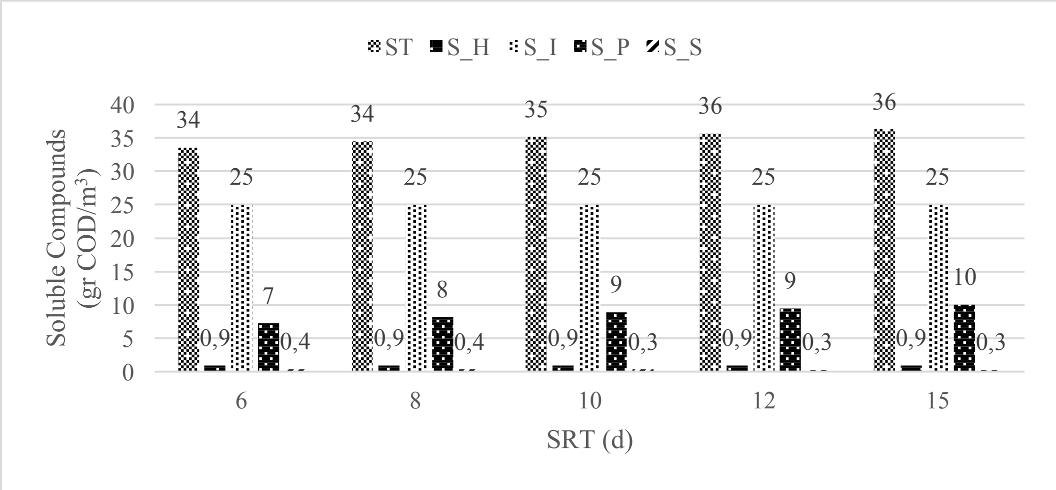

Figure 4.2 : Soluble compounds in the effluent of the CAS system (HRT=8 hr).

Regarding the particulate compounds in the system, it has been noticed that active biomass concentration was increased from 2234 gr COD/m^3 to 3110 gr COD/m^3 with the increase of SRT from 6 to 15 days. The X_S concentrations in the reactor decreased from 54 gr COD/m^3 to 47 gr COD/m^3 depending on the sludge age. Actually X_S was depleted to a large extent, with approximately 99% removal. The values obtained in Figure 4.3 directly indicated the accumulated concentrations in the reactor. The X_I concentrations were accumulated in accordance with SRT/HRT ratio and it can be seen that X_I values were increased from 896 gr COD/m^3 to 2242 gr COD/m^3. Particulate microbial product concentrations, X_P, that originated from biological activity were increased from 389 gr COD/m^3 to 1353 gr COD/m^3 with respect to sludge age increase. The comparison between the lowest and highest sludge ages indicated approximately an X_T increase of 90% (Figure 4.3).

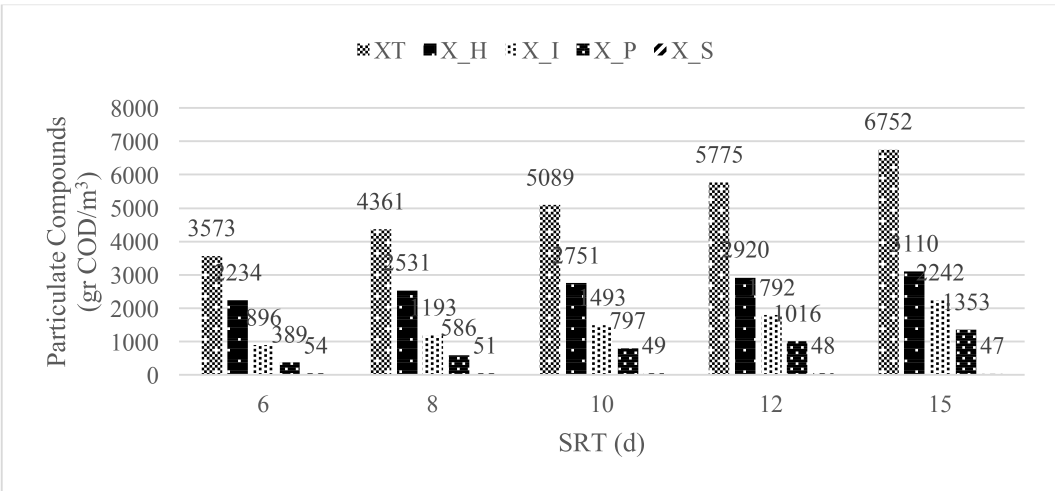

Figure 4.3 : Particulate compounds in the effluent of the CAS system (HRT=8 hr).

As expected from a CAS process regarding the equation (4.22), the sludge generation was decreased enormously when the sludge age was increased from 6 to 15 days. This was actually the reason for operating the activated sludge systems at an extended mode. It should be noted that high SRT, as 15 days, ended up with the lowest active biomass concentration as a result of the dominant endogenous respiration.

Figure 4.4 illustrates the detailed composition of the wasted sludge. For the CAS system, increasing the operational SRT from 6 to 15 d, will decrease the total sludge generation, P_{XT}, from 1939 kg COD/d to 1441 kg COD/d, a reduction of 25%. The active biomass production in the system, P_{XH}, was decreased 1215 kg COD/d to 629 kg COD/d, around 48%, while P_{XP} was increased with 39% from 225 kg COD/d to 313 kg COD/d. Inert fraction of sludge generation, P_{XI}, remained constant for the selected SRT values.

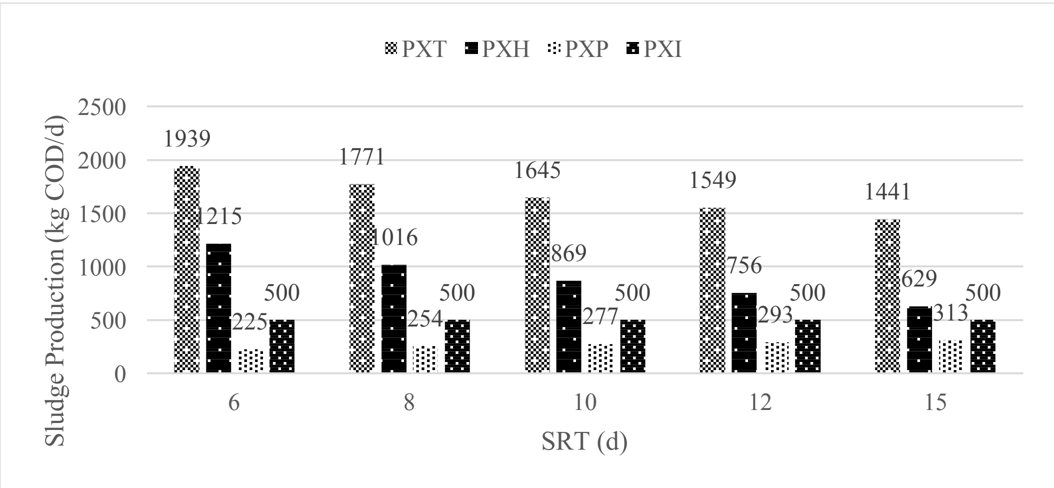

Figure 4.4 : Sludge production in CAS system (HRT=8 hr).

The model results presented that the steady state conditions in CAS were achieved for different recycle (Q_R) and sludge wastage (Q_W) flow rates for each SRT (Table 4.1).

Table 4.1 : Operational conditions of CAS (HRT=8 hr).

SRT (d)	6	8	10	12	15
Q_R (m^3/d)	6837	6938	6999	7039	7080
Q_W (m^3/d)	558	419	335	279	223

The second run was completed with an HRT of 5 hours with a reactor volume of 2100 m^3.

It was noticed that the total soluble compounds in the smaller CAS system were deviated between 34 to 37 gr COD/m^3 with the increase of the SRT from 6 to 15 days, showing the same removal rate obtained for the HRT of 8 hours. Soluble biodegradable substrate, (S_H+S_S), was entirely removed as a result of biological activity, and the total soluble concentration consisted of the inert fraction and the produced products.

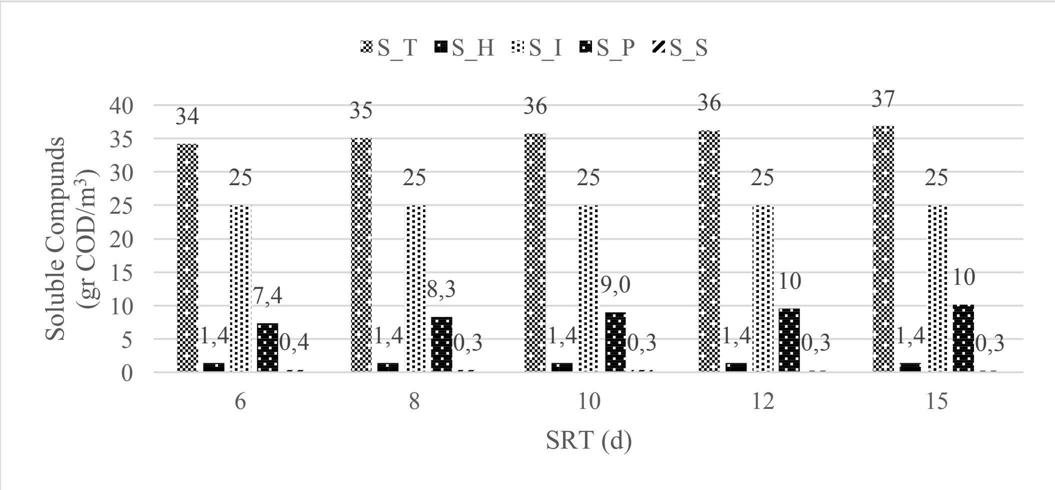

Figure 4.5 : Soluble compounds in the effluent of the CAS system (HRT=5 hr).

Reducing the volume by approximately 40% resulted that the total particulate compounds were increased from 5605 to 10604 gr COD/m^3. In other words, X_T concentration in the CAS was approximately doubled from 6 d SRT to 15 d SRT for the HRT of 5 days (Figure 4.6).

From the engineering point of view it is not possible to operate a CAS system with a X_T concentration higher than 4000 gr TSS/m^3 or 6000 gr COD/m^3. This means that the CAS system cannot be operated for an SRT higher than 6 at an HRT of 5 hours due to the settling problems in the sedimentation tank.

Figure 4.7 was only prepared to demonstrate that there was not a big difference noticed in the amount of the produced sludge for two different HRTs.

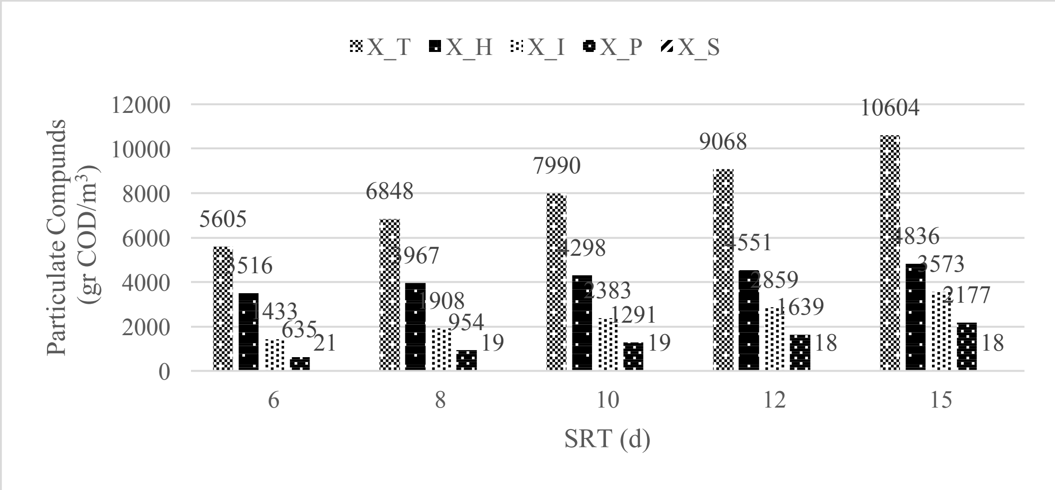

Figure 4.6 : Particulate compounds in the effluent of the CAS system (HRT=5 hr).

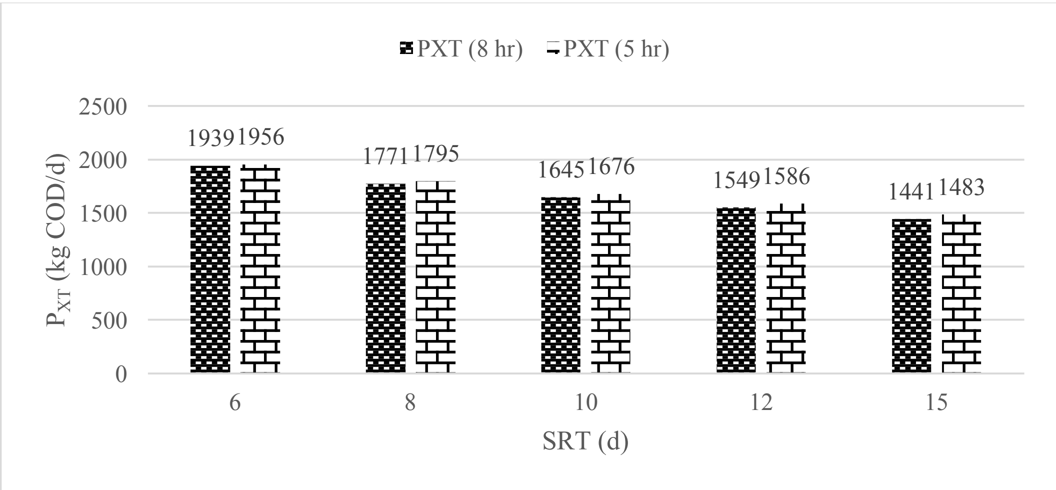

Figure 4.7 : Total sludge generation in CAS systems.

Return activated sludge (Q_R) and sludge wastage (Q_W) flow rates obtained for steady state conditions were tabulated in Table 4.2.

Table 4.2 : Operational conditions of CAS (HRT=5 hr).

SRT (d)	6	8	10	12	15
Q_R (m^3/d)	4825	4869	4895	4912	4930
Q_W (m^3/d)	349	262	210	175	140

Modelling studies on CAS system showed that the increase of the sludge age from 6 days to 15 days reduced the total sludge production approximately 25%, and the meaningful reduction was in the active biomass with a level of 50%, where a remarkable stabilization of organic matter was observed for 8 hours HRT. It is obvious that increasing the SRT as an operational parameter has a limitation due to the feasibility reasons. It seems only applicable to small treatment plants, where the sludge is aerobically stabilized within the activated sludge system.

4.2 Oxic-Settling-Anaerobic System

Process Scheme

The oxic-settling-anaerobic (OSA) process is a modification of the conventional activated sludge (CAS) process where an anaerobic reactor in the excess sludge line is inserted and this line is recirculated to the aeration reactor. This anaerobic tank functions like an external stabilization reactor for the excess sludge (Figure 2.5).

In the modeling, OSA system was simplified by representing the performance of the anaerobic stabilization with a fictive intrusion of active biomass into the aerobic reactor (Figure 4.8).

The simplification based on the assumption that excess sludge has been stabilized elsewhere and is returned to the system as a viable heterotrophic active biomass, X_{H1}. Mass balance of the modified OSA system was made based on this assumption.

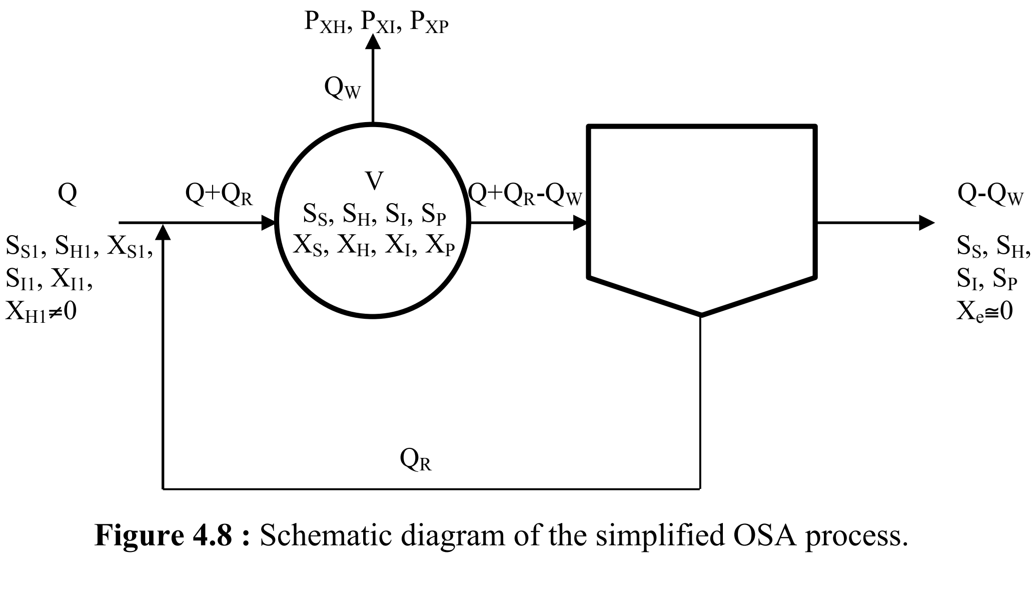

Figure 4.8 : Schematic diagram of the simplified OSA process.

The mass balance on substrate removal for OSA is written in a similar way to CAS as given in equation (4.1).

The mass balance for active heterotrophic biomass in the OSA process differed from the CAS by an initial active biomass intrusion:

$$Q\,X_{H1} - Q_W X_H + V\,X_H\,(\mu_H - b_H) = 0 \tag{4.32}$$

If the excess sludge is defined as;

$$P_{XH} = Q_W X_H \tag{4.33}$$

$$P_{XH} = \frac{V\,X_H}{SRT} \tag{4.34}$$

The net growth rate can be derived from equation (4.32);

$$(\mu_H - b_H) = \frac{1}{SRT} - \frac{1}{HRT}\,\frac{X_{H1}}{X_H} \tag{4.35}$$

As a difference from the CAS this equation indicates, that the net growth rate is not controlled by the SRT alone. Using the definition in equation (4.2), and inserting equation (4.35) in equation (4.1), the biomass concentration in the reactor (X_H) is calculated as a function of the initial heterotrophic biomass (X_{H1}) with the assumption that the biodegradable substrate is totally utilized:

$$X_H = \frac{Y_H}{1+b_H\,SRT}\,C_{S1}\,\frac{SRT}{HRT} + \frac{1}{1+b_H\,SRT}\,X_{H1}\,\frac{SRT}{HRT} \tag{4.36}$$

$$X_H = [Y_H C_{S1} + X_{H1}]\left[\frac{1}{1+b_H\,SRT}\,\frac{SRT}{HRT}\right] \tag{4.37}$$

This expression indicates that the biomass concentration in the reactor is significantly increased by the initial biomass concentration.

This way, the net active biomass generation, P_{XHN}, can be obtained combining equations (4.1) and (4.37):

$$P_{XHN} = Q\,Y_H\,C_{S1} - Q\frac{Y_H}{1+b_H\,SRT}\,C_{S1}\,b_H\,SRT - Q\,\frac{X_{H1}}{1+b_H\,SRT}\,b_H\,SRT \tag{4.38}$$

This expression reveals an other difference from the CAS system. In CAS systems the active biomass level sustained in the reactor, ($V\,X_H$) is determined by the influent substrate level C_{S1} and the selected SRT, and the net active biomass generation P_X is conveniently defined in terms of a net sludge yield, $Y_{HN:}$

$$P_{XH} = Y_{NH}\,Q\,C_{S1} \tag{4.39}$$

where,

$$Y_{NH} = \frac{Y_H}{1+b_H\,SRT} \tag{4.40}$$

However, due to the X_{H1} intrusion, the biomass accumulates in the OSA process and endogenous respiration undergoes higher level. As a result of the high endogenous respiration, P_{XHN} becomes significantly reduced:

$$P_{XHN} = Y_{OBS}\, Q\, C_{S1} \tag{4.41}$$

where, $Y_{OBS} < Y_{NH}$.

Expressing the observed yield, Y_{OBS}:

$$Y_{OBS} = \frac{\mu_H - b_H}{\mu_H / Y_H} = Y_H\left(1 - \frac{b_H}{\mu_H}\right) \tag{4.42}$$

Depending on the magnitude of X_{H1}, μ_H may fall below b_H ($\mu_H < b_H$) i.e. net growth and Yobs may be negative. Obviously, this would indicate a transition period where the system would reach another steady state with a lower X_H concentration in the reactor.

Other sludge fractions can be calculated as:

$$P_{XP} = f_{ex} b_H P_{XH} SRT \tag{4.43}$$

$$P_{XI} = Q\, X_I \tag{4.44}$$

Finally, total biomass in the system, P_{XT};

$$P_{XT} = P_{XHN} + P_{XP} + P_{XI} \tag{4.45}$$

Sludge wastage (Q_W) and return activated sludge (Q_R) flow rates were calculated manually to maintain the desired SRT for both OSA and CS processes according to equations (4.30) and (4.31).

Results

The results of modeling for OSA reflected the features of the classical activated sludge system with an initial active biomass. The volume of the reactor was selected as 3350 m^3 yielding an HRT of 8 hours (0.335 days).

The modelling study was performed to reflect the impact of the initial active biomass concentration, X_{H1}, and the sludge retention time, SRT. Their effects on the concentrations of the total soluble organics S_T, total particulates X_T, net sludge generation P_{XHN}, total excess sludge P_{XT}, and total observed yield Y_{OBS}, were given in Figure 4.6, 4.7, 4.8, 4.9 and 4.10, respectively. The results of CAS process were also displayed in the same figure with no initial input of X_{H1}.

Total soluble compounds, S_T, as a sum of S_S, S_H, S_I and S_P, reflected a slight increase for all inputs of X_{H1} at different SRTs (Figure 4.9). The simulation representing the CAS system had a soluble effluent quality 34 gr COD/m^3 at SRT 6 increasing up only to 36 gr COD/m^3 at SRT 10 days. The highest concentrations were noticed for the case of 200 gr cell COD/m^3 input, where 39 gr COD/m^3 and 44 gr COD/m^3 were obtained at SRT 6 and 10 days, respectively. The increase in soluble compounds was the consequence of the S_P generation depending on the sludge age.

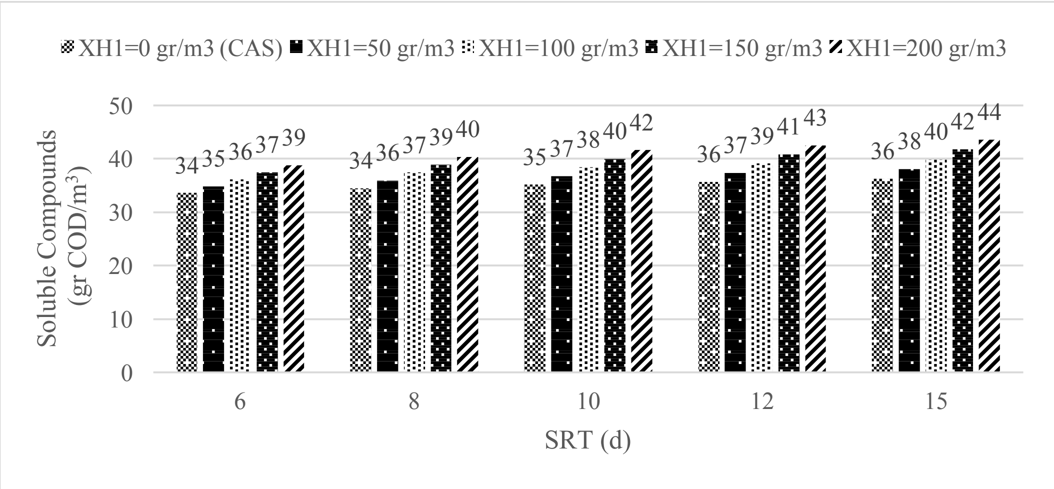

Figure 4.9 : Soluble compounds in the OSA effluent depending on the initial biomass.

Considering the total particulate compounds it was noticed that CAS could held approximately a concentration of 3570 gr COD/m^3 at an SRT of 6 days, whereas this value was increased up to 6750 gr COD/m^3 at SRT 15 days. An initial biomass concentration of 100 gr cell COD/m^3 resulted approximately in an increase of 25% increase of the particulates in the reactor, whereas it has been doubled for 200 gr cell COD/m^3 input (Figure 4.10).

The simulation for the net sludge generation for different initial X_{H1} is illustrated in Figure 4.11. It was an interesting observation that an initial biomass concentration of 200 gr cell COD/m^3 caused a negative sludge production starting from the SRT of 8 days as given in equation (4.40). It was the result of the increase of the endogenous decay level in comparison to growth level due to the high accumulated amount of biomass in the reactor. The same effect was noticed even for an initial biomass of 150 gr cell COD/m^3 starting at an SRT of 10 days.

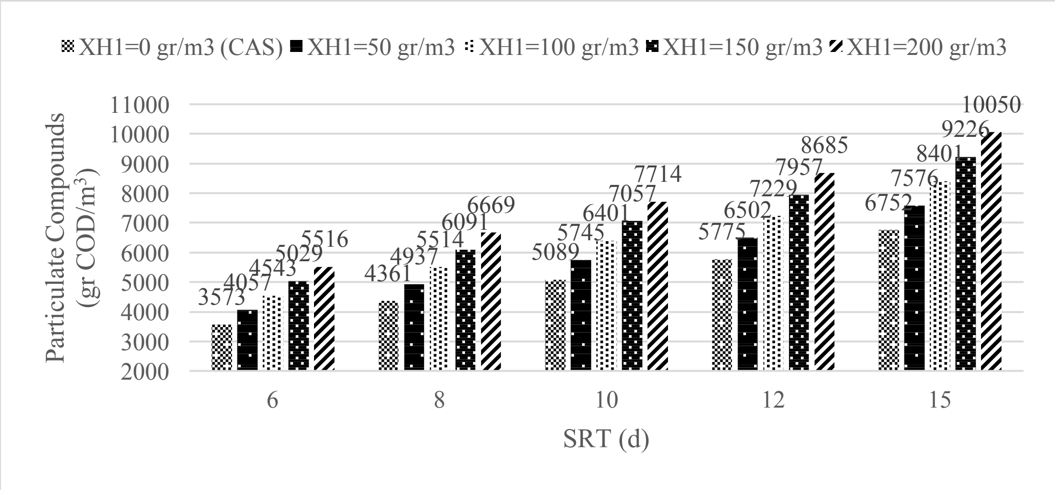

Figure 4.10 : Particulate compounds in the OSA effluent depending on the initial biomass.

In other words, higher active biomass concentrations in the reactor result in two major changes in corresponding biochemical processes: (i) Under the same available substrate level, the microbial growth rate, μ is proportionally reduced (ii) The relative magnitude of the endogenous decay (not the endogenous decay rate) is significantly increased with respect to microbial growth, since it is no longer controlled by the substrate input and the selected sludge age. Both changes lead to a much lower observed yield, Y_{OBS} value as compared to the Y_{HN} level in the control reactor, resulting in a much lower net sludge generation.

In CAS increasing the SRT from 6 days to 10 days graded a decrease of 50% in sludge production. In OSA, an input of 50 gr cell COD/m^3 in the influent was sufficient to yield a 75% reduction, whereas a 100 gr cell COD/m^3 ended up approximately with a 100% reduction. In this case, the wasted sludge consisted of only the initial biomass load (Q X_{H1}).

The results of the simulation proved that enhanced endogenous decay due to higher active biomass level sustained in the OSA reactor should be regarded as the major cause of excess sludge reduction in the OSA system.

The steady state simulation confirmed a relationship between the compound and flowrates as indicated in Table 4.3.

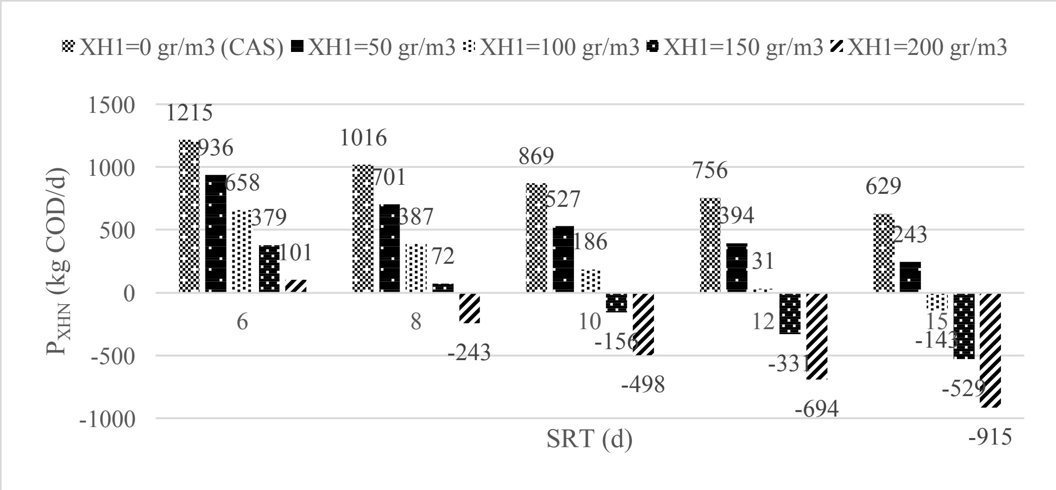

Figure 4.11 : Net sludge generation in OSA system.

Table 4.3 : Operational conditions for modified OSA.

SRT (d)	6	8	10	12	15
Q_R (m^3/d)	6837	6938	6999	7039	7080
Q_W (m^3/d)	558	419	335	279	223

Total sludge generation was illustrated in Figure 4.12. According to this figure, in the CAS system total sludge reduction was around 26%. With the X_{H1} input, net sludge generation cannot be observed for a certain X_{H1} and specific SRT. This is an indication that the active biomass will no longer be a part of total sludge generation. Total sludge production was decreased at a considerable extent.

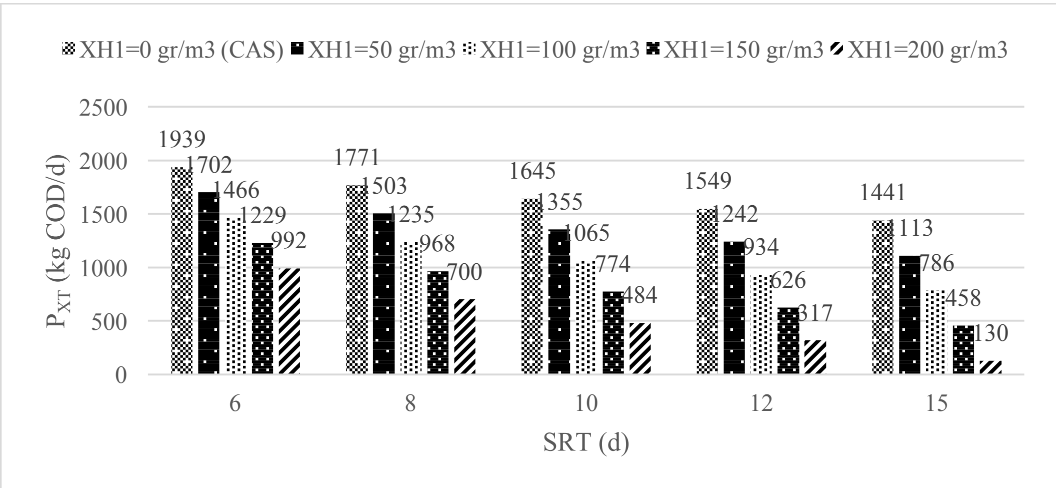

Figure 4.12 : Total sludge generation in OSA system.

Depending on the equation 4.42 the observed yield, Y_{OBS}, was also decreased with the increase of SRT and X_{H1} input. Such that, Y_{OBS} could reach a negative value for SRTs greater than 10 d and 150 gr COD/m^3 X_{H1} input to the system (Figure 4.13).

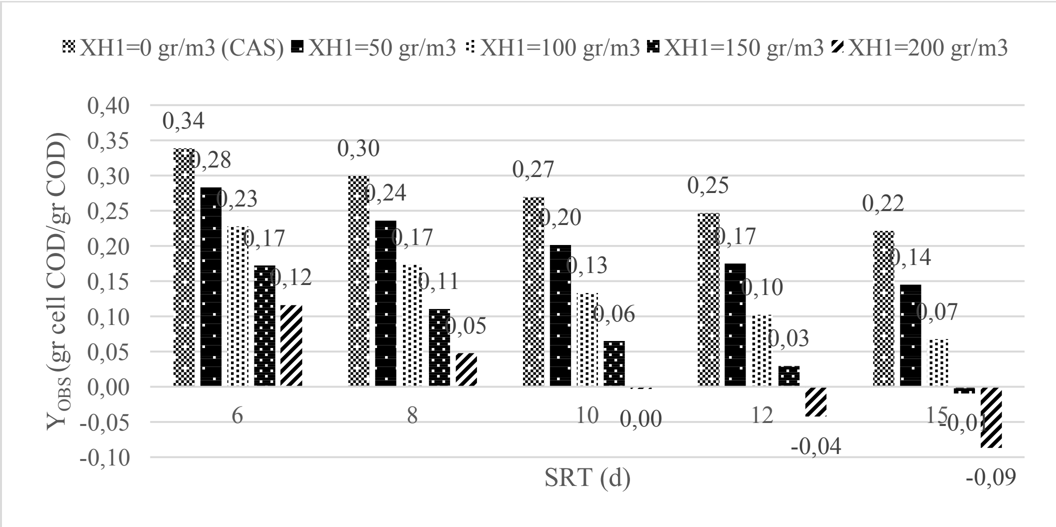

Figure 4.13 : Observed yield in OSA system.

In summary, the simulations showed that an SRT for 8 days and X_{H1} input of 200 gr COD/m^3 can be considered as sufficient to enough to prevent the biomass generation.

4.3 Contact Stabilization System

Process Scheme

The contact stabilization (CS) process is a modification of the conventional activated sludge (CAS) process where an aerobic stabilization reactor is located at the return activated sludge line and the effluent of this reactor is recirculated to the contact reactor. This aerobic tank functions like a side-stream stabilization reactor for the returned sludge (Figure 4.14).

This configuration provides to keep the same amount of sludge at lower volumes compared to CAS because the stabilization tank manages to have the settled sludge in a more concentrated form.

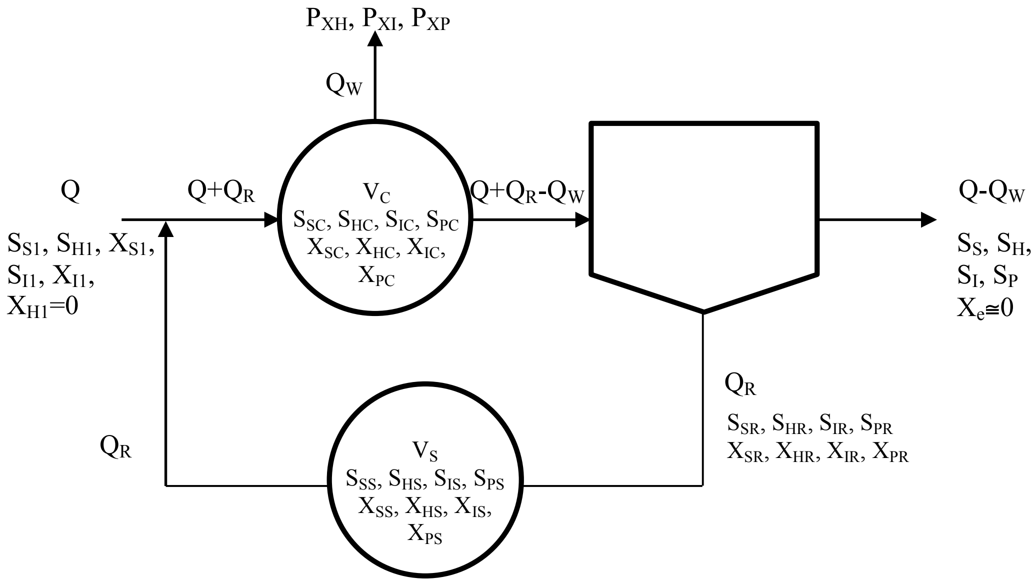

Figure 4.14 : Schematic diagram of the CS process.

The contact reactor (CR) is designed at a very low HRT just to allow the removal of soluble substrate compounds, where the stabilisation reactor (SR) is devoted for the removal of the particulate substrate and the sludge stabilisation.

Substrate balance for the contact reactor can be written with the assumption that all biodegradable subsrate, S_{S1} and S_{H1}, is utilized;

$$Q\,(S_{S1} + S_{H1}) - \frac{1}{Y_H}\mu_H V_C X_{HC} = 0 \tag{4.46}$$

where, V_C is the volume of the contact reactor and X_{HC} is the active biomass concentration in the contact reactor.

A similar mass balance for substrate utilization can be written for the stabilization tank, even with the assumption that all particulate substrate is removed in the reactor:

$$Q\,X_{S1} - \frac{1}{Y_H}\mu_H V_S X_{HS} = 0 \tag{4.47}$$

where, V_S is the volume of the stabilisation tank and X_{HS} is the active biomass concentration in the stabilisation tank.

As a result of these two equations, the mass balance for the utilisation of the total biodegradable substrate yields as:

$$Q\,C_{S1} - \frac{1}{Y_H}\mu_H V_C X_{HC} - \frac{1}{Y_H}\mu_H V_S X_{HS} = 0 \tag{4.48}$$

The total amount of sludge (M_{XT}) distributed among the two reactors is a key parameter as given in equation (4.49),

$$M_{XT} = V_C X_{TC} + V_S X_{TS} \tag{4.49}$$

where the X_{TC} and X_{TS} reflects the total particulate compouds in both CR and SR, respectively and expressed with a fraction of α for the contact reactor:

$$\alpha = \frac{V_C\,X_C}{V_C\,X_C + V_S\,X_S} \tag{4.50}$$

and β for the stabilization tank:

$$\beta = \frac{V_S\,X_S}{V_C\,X_C + V_S\,X_S} \tag{4.51}$$

The sludge generated in the system may be estimated by selecting SRT:

$$P_{XT} = M_{XT}\ \mathrm{SRT} \tag{4.52}$$

The components of the sludge consist of active biomass, generated microbial product and inert fraction in both CR and SR.

The active biomass,

$$P_{XHC} = Y_H Q(S_{S1} + S_{H1}) \tag{4.53}$$

generated microbial product, with the assumption that there is only growth in the CR:

$$P_{XPC} = f_{ex} b_H V_C X_{HC} = 0 \tag{4.54}$$

are considered as the sludge components in the contact reactor.

Regarding the stabilisation tank, the same sludge components may be estimated with the following equations.

$$P_{XHS} = Y_H Q X_{S1} - b_H V_S X_{HS} \tag{4.55}$$

$$P_{XPS} = f_{ex} b_H V_S X_{HS} \tag{4.56}$$

And for the whole system; inert fraction originated from the wastewater;

$$P_{XI} = Q\,X_{I1} \tag{4.57}$$

The total biomass for the CS system;

$$P_{XT} = P_{XHC} + P_{XPC} + P_{XHS} + P_{XPS} + P_{XI} \tag{4.58}$$

$$P_{XT} = Y_H Q(S_{S1} + S_{H1} + X_{S1}) - b_H V_S X_{HS} + f_{ex} b_H (V_C X_{HC} + V_S X_{HS}) + Q X_{I1} \quad (4.59)$$

Sludge wastage (Q_W) and return activated sludge (Q_R) flow rates were obtained to maintain the desired SRT for CS processes.

Results

CS system was designed to have a CR with a very short HRT at a very small volume aiming only the removal of soluble substrate and an aerobic reactor added in the recirculation line to examine the possible effect on the sludge reduction. First, the system was designed to be compared to the operational conditions of CAS by selecting a similar total HRT of 8 hours, where a very short HRT of 45 minutes was allocated to CR. The volumes were adjusted to 300 m^3 for CR and 3000 m^3 for SR, as a total of 3300 m^3.

In the second run, the total HRT was reduces to 5 hours to outline the effect of system behaviour on the sludge production. The HRT was divided as 30 minutes and 4.5 hours to CR and SR, respectively. In this case the total volume was reduced to 2100 m^3, shared as 200 m^3 by CR, 1900 m^3 by SR.

The recycled and wasted sludge flowrates (Q_R and Q_W) were adjusted for providing desired SRT.

The results of the first run indicated that an HRT of 45 minutes was managed to end up with a total soluble substrate concentration of 66 gr COD/m^3 for SRT of 6 days, where it has been reduced to 58 gr COD/m^3 for SRT of 15 days. The soluble components mostly consisted of S_P and S_I. S_P was not generated in the CR because no decay process was considered, but the concentration increased by the accumulation raised from the recirculation.

It was evident from the results that the biodegradable soluble substrate was almost removed for each SRT with an average efficiency of 90% (Figure 4.15).

The total particulate compounds in the CR were increased with the increase of SRT, as expected. X_T concentration was increased by 78% from 1476 to 2620 gr COD/m^3, where X_H took a part of 43% and X_P of 30%, X_S and X_I not effective on the increase at all (Figure 4.16).

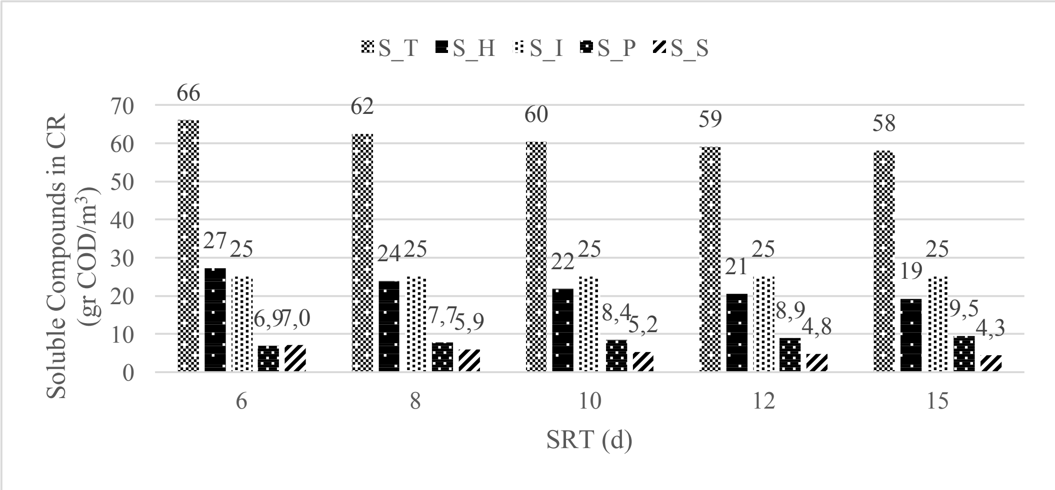

Figure 4.15 : Soluble compounds in CR (HRT_C=45 min, HRT=8 hr).

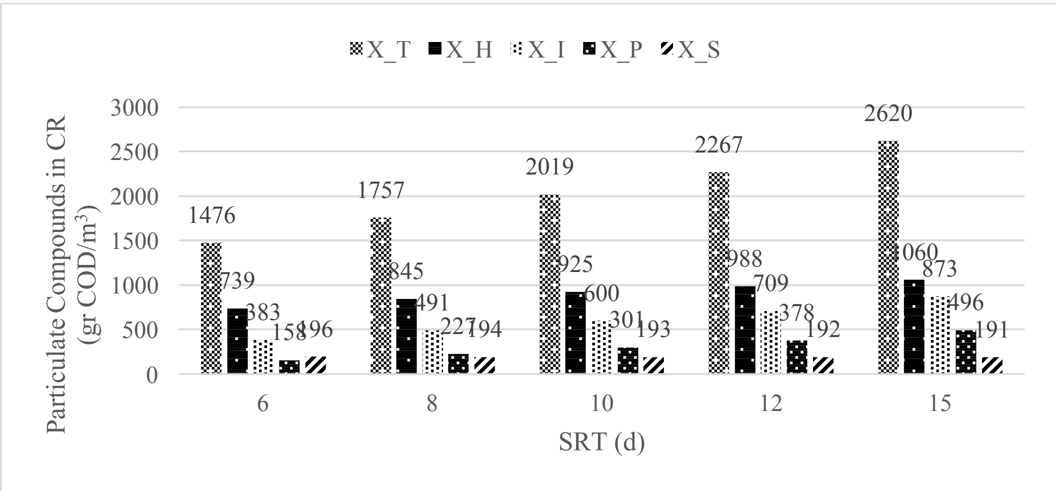

Figure 4.16 : Particulate compounds in CR (HRT_C=45 min, HRT=8 hr).

Regarding the soluble compounds in the stabilization tank, it was obvious that the remaining part of soluble substrate from contact reactor was utilized together with the particulate substrate.

A further reduction of approximately 17% was achieved in SR for soluble compounds (Figure 4.17). The soluble compounds mainly composed of S_I and S_P productions due to the decay process.

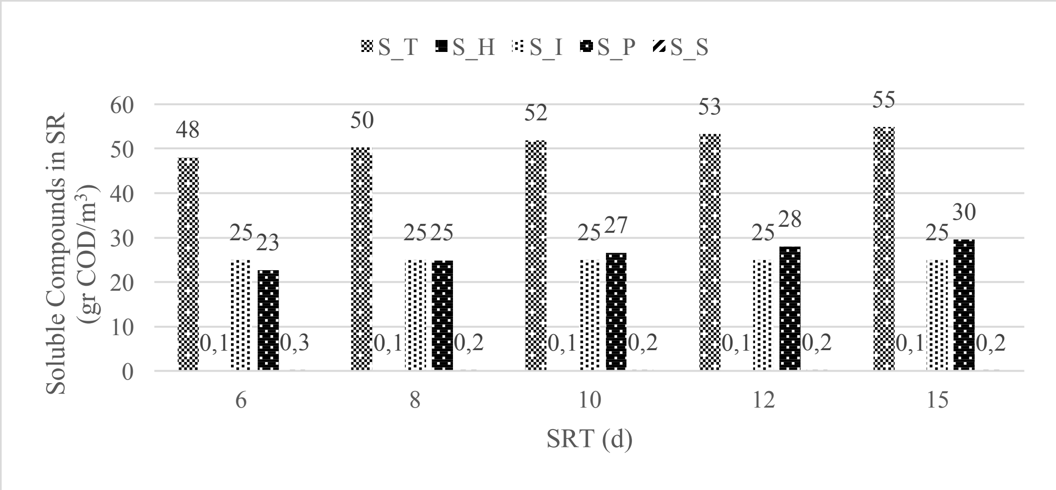

Figure 4.17 : Soluble compounds in SR (HRT_S=7.2 hr, HRT=8 hr).

The total biomass concentration in the stabilization reactor was assumed to be approximately 3 times the total biomass concentration in the contact reactor with respect to the operation of the settling tank and the sludge distribution fraction.

The modeling results indicated that the total particulate compounds in SR ranged between 3974 and 7333 gr COD/m^3 depending on the SRT from 6 to 15 days (Figure 4.18). As a result of biological activity in SR, including growth, hydrolysis and decay mechanisms, active biomass concentration was increased 2290 to 3154 gr COD/m^3, which was approximately 40%. SR mainly used slowly biodegradable fraction of COD as substrate, so that X_S, was depleted at a large extent, only observed in a concentration of 12 gr COD/m^3 accumulated in the reactor.

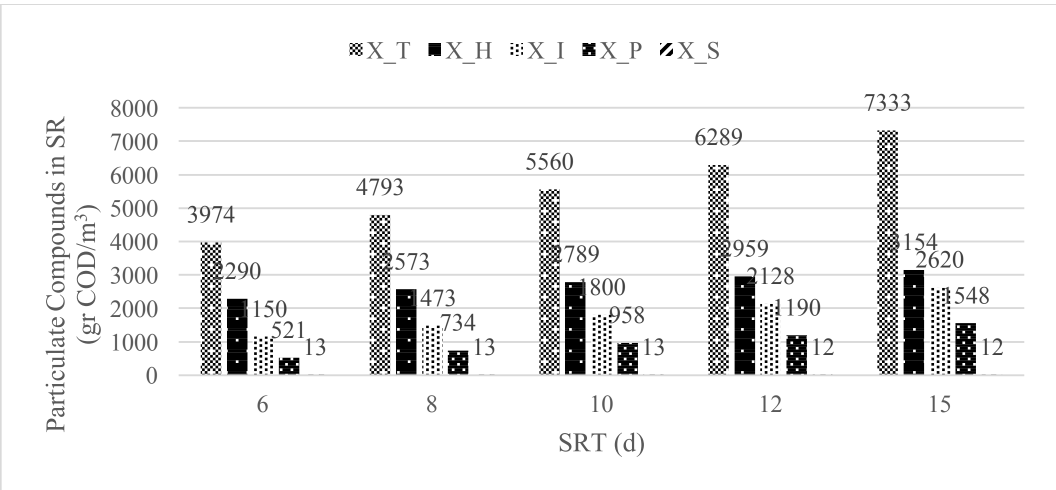

Figure 4.18 : Particulate compounds in SR (HRT_S=7.2 hr, HRT=8 hr).

The system reached the steady state conditions for the flowrates indicated in Table 4.4.

Table 4.4 : Operational conditions of CS (HRT=8 hr).

SRT (d)	6	8	10	12	15
Q_R (m^3/d)	4348	4491	4583	4648	4713
Q_W (m^3/d)	1305	1018	833	705	573

Contact stabilization process was also modelled in the second run with a total HRT of 5 hours to compare the difference of the system performance with the longer HRT trial. Thus, reactor volumes were reduced to 200 m^3 and 1900 m^3 for the CR and SR, respectively, so that an HRT of 30 minutes was sustained in CR and 4.5 hours in SR.

The results for CR showed that the removal of the total soluble compounds was slightly decreased compared to 8 hours HRT. Total soluble substrate was removed approximately 80% and total soluble compounds in the CR was obtained 65 gr COD/m^3 for the sludge ages investigated (Figure 4.19).

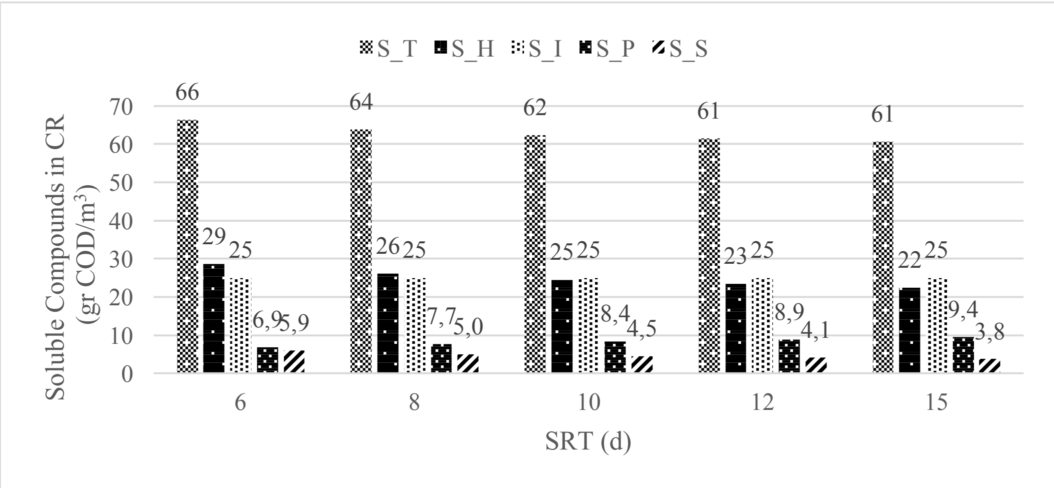

Figure 4.19 : Soluble compounds in CR (HRT_C=30 min, HRT=5 hr).

Regarding the particulate compounds in CR, the only mechanism to increase the particulates was mainly the recirculated compounds from SR, since the growth was associated with only the soluble substrate at a very short HRT. Thus, the particulates were fluctuated from 2197 to 3958 gr COD/m^3 (Figure 4.20). Active biomass concentration was increased almost four times for SRTs ranging from 6 to 15 days.

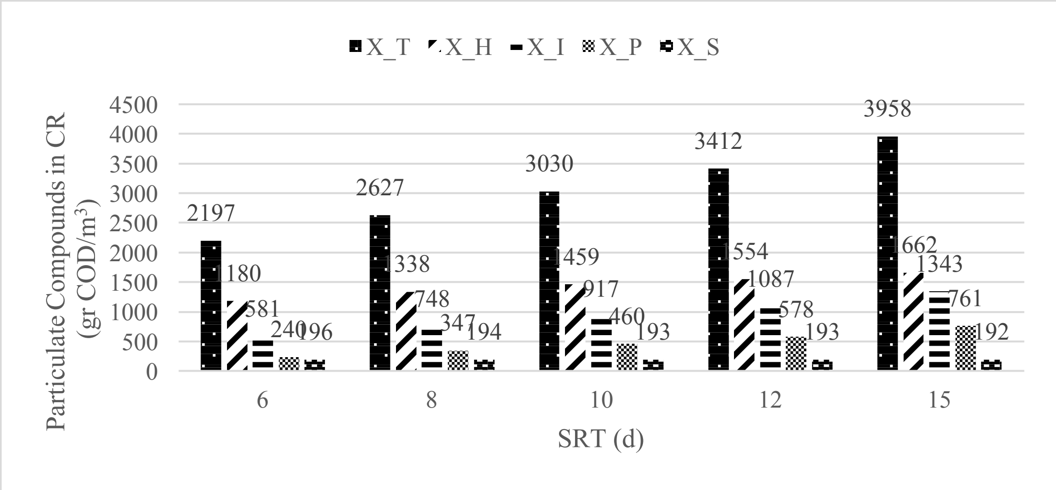

Figure 4.20 : Particulate compounds in CR (HRT_C=30 min, HRT=5 hr).

Total solubles were further reduced in the SR, yielding a range of 47 gr COD/m^3 to 54 gr COD/m^3 (Figure 4.21). The same trend was achieved in the 2nd run, with the conclusion that soluble compouns did not reflect any major difference depending on the reduction of HRT. This is an indication of the high effective performance of the CR at an adequate HRT.

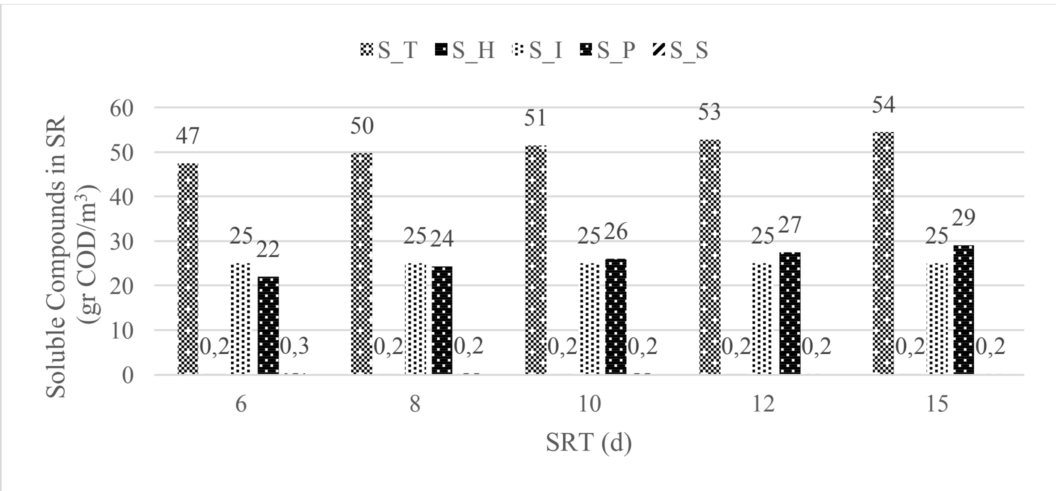

Figure 4.21 : Soluble compounds in SR (HRT_S=4.5 hr, HRT=5 hr).

The concentrations of the particulate compounds were found higher than the concentrations yielded at 8 hours HRT as a result of the reduction of the volume. Total particulate concentrations were increased approximately 50% with the decrease of the volume approximately %35. Total concentration in the SR was predominantly composed of X_H and reflecting that the X_S was majorly removed within the system (Figure 4.22).

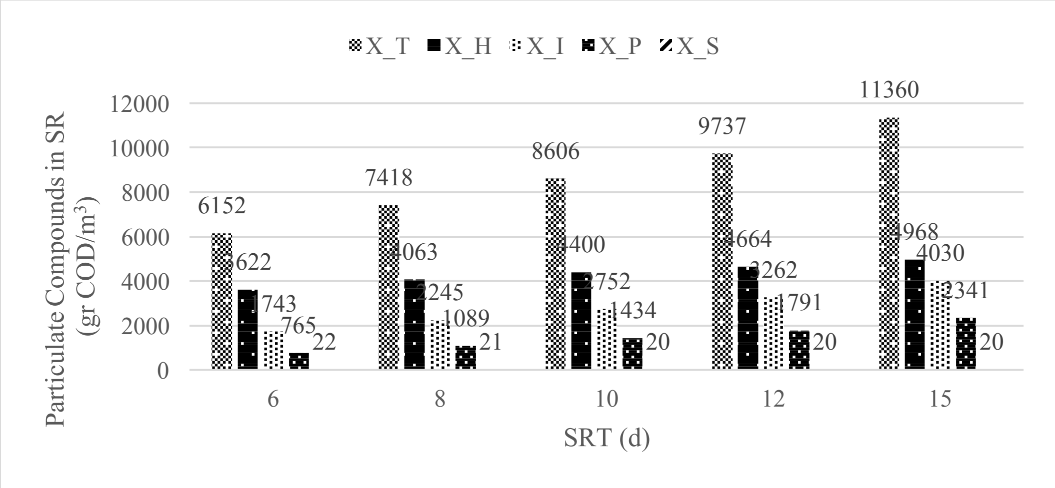

Figure 4.22 : Particulate compounds in SR (HRT_S=4.5 hr, HRT=5 hr).

Table 4.5 reflects the operational conditions of CS process for 5 hours HRT.

Table 4.5 : Operational conditions of CS (HRT=5 hr)

SRT (d)	6	8	10	12	15
Q_R (m^3/d)	4569	4666	4727	4770	4813
Q_W (m^3/d)	861	668	545	460	372

First of all, the CS process with two different HRTs were compared in terms of the sludge production. They were compared with CAS to evaluate the extent of sludge reduction of both configurations (Figure 4.23). CS process with the total HRTs of 5 hours and 8 hours were compared with CAS with an HRT of 8 hours in terms of the sludge production. HRT for 5 hours was not considered in the evaluation with the fact that the produced mass in the reactor cannot be settled in the conventional settling tank due to the solid flux limitation.

The total sludge production, in other words the excess sludge to be further treated in a sludge treatment facility was found approximately the same for CAS with an HRT of 8 hours compared to CS with HRTs of 8 and 5 hours. The reason of having mostly the same sludge amount in CAS and CS araised from the fact that the amount of sludge remained the same in CS as a result of the raised concentration in the decreased volume. Namely, decreasing the HRT was increasing the concentration of the particulates yielding the generation of the same amount of sludge at significantly lower volumes.

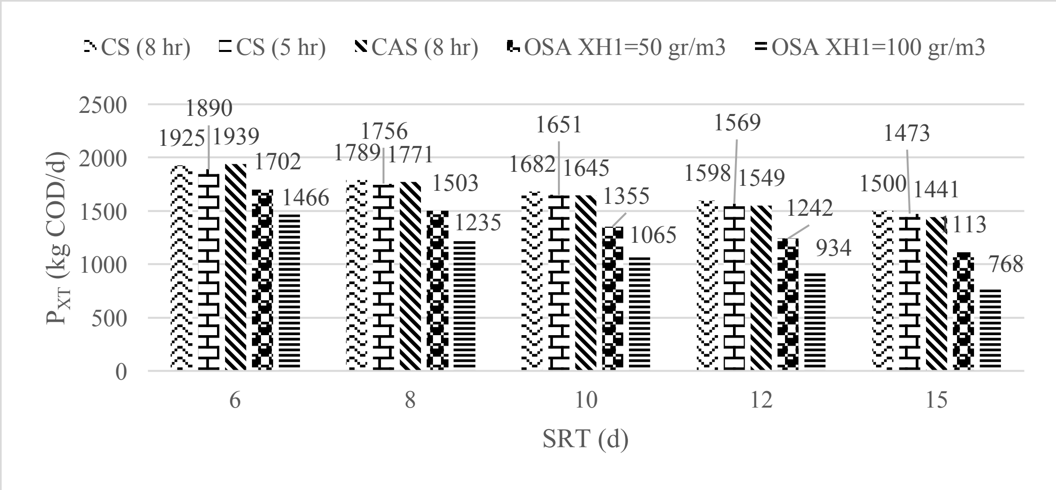

Figure 4.23 : Total sludge generation for different HRTs.

The results showed that there was not a big difference in sludge production as a result of reducing the volumes and concentrating the particulates, so that yielding mostly the same amount of the sludge mass. But the interesting point in the view of engineering is that the same amount of sludge was achieved with a reduced volume of approximately 35%. This was an indication of approximately the same amount of biomass sustained in the system regardless of the adequate HRT. This means, on the other hand, that CS performed the same effluent quality for both soluble and particulate forms in a half of the volume required for CAS. However, in the OSA system, considerably lower sludge generation was observed even for the 50 gr cell COD/m^3 active biomass intrusion. Reduction of sludge generation was around 17% for 50 gr cell COD/m^3 X_{H1} entrance to the OSA system for SRTs from 6 d to 15 d. When the concentration of biomass that given to the influent stream was increased to 100 gr cell COD/m^3, sludge minimization ratio increased to 35% for selected SRTs.

Observed yield was also changed within a short range in conjunction with the same activated sludge production when CS process compared to CAS (Figure 4.24). Y_{OBS} was fluctuated averagely from 0.48 gr cell COD/gr COD to 0.36 gr cell COD/gr COD for SRT changing 6 days to 8 days in the CS and CAS. Nevertheless, in the OSA process it was observed that net yield was significantly lower when compared to CAS process. Observed yield was decrased approximately 50% and 60% for 50 gr cell COD/m^3 and 100 gr cell COD/m^3 X_{H1} input, respectively to the system for selected SRTs.

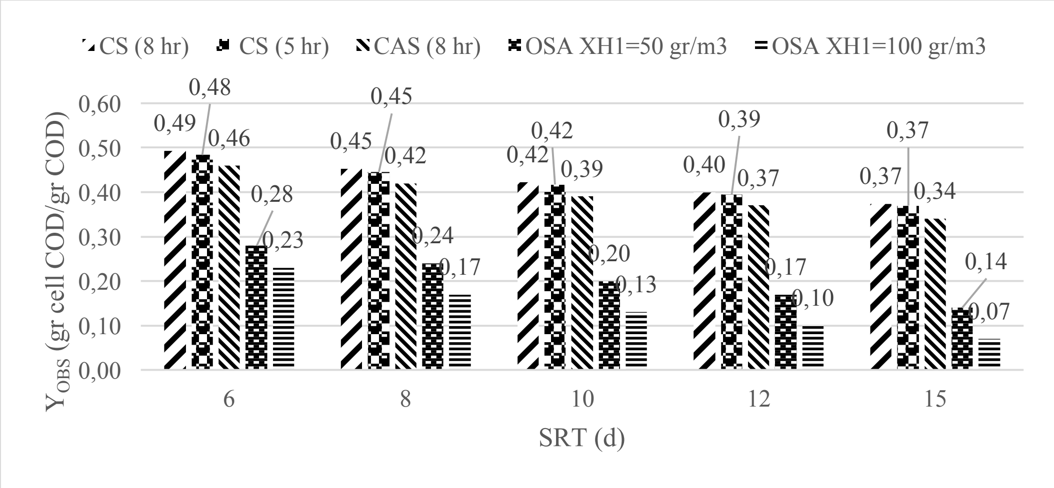

Figure 4.24 : Observed yield for different HRTs.

5. CONCLUSION AND RECOMMENDATIONS

This thesis aimed to evaluate the merit of the modified activated sludge systems in terms of sludge production. The study has been structured on a model based evaluation. Simulations were done on the basis of the modified ASM1 by using the AQUASIM software for different operational conditions.

Modifications of the activated sludge system providing an increase in the endogenous decay level were investigated to achieve a reduction in excess sludge production. Two different process alternatives, (i) a system with active biomass in the influent, and (ii) a system equipped with a separate reactor with sludge re-aeration, were modelled within the scope of this study. The first alternative was represented by oxic-settling anaerobic (OSA) process that consists of an aerobic biological reactor operated at a selected sludge age with an anaerobic unit that receives the excess sludge and recycles back to the influent stream after stabilization. The second alternative was the contact stabilization (CS) equipped with a very small aerated contact tank for the removal of soluble substrate and a much larger aerated stabilization tank located in the recirculation line for the re-aeration of the produced sludge in the contact tank. The evaluation was conducted by a systematic comparison of these two modifications with the conventional activated sludge (CAS) system.

The main observations concerning the OSA system may be summarized as follows: The sludge reduction achieved in the system can be explained on the basis of active heterotrophic biomass input to the aerobic reactor when compared with CAS system. An input of 50 gr cell COD/m^3 initial active biomass reduced the total sludge production approximately in a range of 12-22% with the increase of SRT from 6 days to 15 days as compared to CAS. Expanding the input to 100 gr cell COD/m^3 approximately doubled the benefit of OSA system in sludge production. The OSA aeration reactor reached a considerable higher active biomass concentration than CAS system as a result of the active biomass input.

Higher active biomass concentrations in the OSA provided that the relative magnitude of the endogenous decay level was significantly increased in comparison to microbial growth level depending on the fact that the growth was no longer controlled by the substrate input and the selected sludge age. Thus, a much lower observed yield, Y_{OBS} value as compared to the Y_{HN} level was observed when compared to CAS, resulting in a much lower net sludge generation. Y_{OBS} values for defining the total sludge production for OSA were found to be approximately 50% less than CAS for an input of 50 gr cell COD/m^3. These values were more reduced with an input of 100 gr cell COD/m^3.

The main observations concerning the CS system may be shortened with the following remarks: CS consisted of two different aeration tanks, one was devoted only to the removal of soluble substrate on the basis of growth process, the other for sludge stabilization functioning for both growth and decay processes.

CS process allowed a significant reduction in the contact tank volume by conducting a part of the aeration on the concentrated sludge underflow, thus holding a larger activated sludge mass than CAS at the same organic loading.

CS enabled the same desired wastewater quality with a much more smaller aeration volume and did not present a meaningful difference in sludge production and Y_{OBS} when compared to CAS. Even CS at different HRTs produced the same amount of sludge at the same SRT. CS has the capability of handling the similar performance at a much higher F/M ratio with the same magnitude of sludge production. The advantage of CS in the practical implication was the ability to reduce the size of the settling tank depending on the reduced solid flux. CS was modelled for constant endogenous decay rate, this should be verified by experimental studies to demonstrate any possible increase of b_H.

As a future perspective, the modifications of activated sludge systems for the sludge reduction may be developed/improved in conducting experimental studies within the view of modelling studies.

REFERENCES

Aasheim, S. E. (1985). Sludge stabilization: Manual of practice No. FD-9. Washington D.C.: Water pollution control federation: Task force on Sludge stabilization.

Alexander, W. V., Ekama, G. A., Marais, G. V. R. (1980). The activated sludge process part 2. Application of the general kinetic model to the contact stabilization process. *Water Research*, **14**, 1737-1747.

Amuda, O. S., Deng, A., Alade, A. O., Hung, Y. T. (2008). Conversion of sewage sludge to biosolids, in *Biosolids engineering and management, Handbook of environmental engineering* (eds) Wang, L.K., Shammas N.K., and Hung Y.T. Humana Press, Totowa.

Appels, L., Baeyens, J., Degrève, J. , Dewil, R. (2008). Principles and potential of the anaerobic digestion of waste-activated sludge, *Progress in Energy and Combustion Science,* **34**, 755-781.

Ardern, E. and Lockett, W. T. (1914). Experiments on the oxidation of sewage without the aid of filters. *Journal Society of Chemical Industries*, **33**, 523-539.

Campos, J. L., Otero, L., Franco, A., Mosquera-Corral, A., Roca, E. (2009). Ozonation strategies to reduce sludge production of a seafood industry WWTP. *Bioresource Technology*, **100**, 1069–73, doi:10.1016/j.biortech.2008.07.056.

Davis, R. D., Hall, J. E. (1997). Production, treatment and disposal of wastewater sludge in Europe from a UK perspective. *European Water Pollution* Control, **7(2)**, 9–17.

Demir, Ö. and Filibeli, A. (2016). The investigation of the sludge reduction efficiency and mechanisms in oxic–settling–anaerobic (OSA) process. *Water Science & Technology*, **73**, 2311-2323, doi:10.2166/wst.2016.076.

Divyalakshmi, P., Murugan, D., Sivarajan, M., Sivasamy, A., Saravanan, P., Lajapathi Rai, C. (2015). In situ disruption approach on aerobic sludge biomass for excess sludge reduction in tannery effluent treatment plant. *Chemical Engineering Journal*, **276**, 130–136, doi:10.1016/j.cej.2015.04.085.

EPA, Environmental Protection Agency (2000). Biosolid technology fact sheet-Alkaline stabilization of biosolids. EPA/832/F-00-052.

Goel, R. K., Noguera, D. R. (2006). Evaluation of sludge yield and phosphorus removal in a cannibal solids reduction process. *Journal of Environmental Engineering*, **132**(10), 1331-1337.

Grady, C. P. L., Daigger, G. T., Lim, H. C. (1998) Biological wastewater treatment. 2nd Edition. Revised and Extended. Taylor & Francis.

Gujer, W., Henze, M., Mino, T., Matsuo, T., Wentzel, M. C., Marais, G. V. R. (1995). The activated sludge model No. 2: Biological phosphorus removal, *Water Science and Technology,* **31**, 1–11.

Gujer, W., Henze, M., Mino, T., Van Loosdrecht, M. (1999). Activated sludge model No. 3, *Water Science and Technology*, **39**, 183–193.

Guo, W. Q., Yang, S. S., Xiang, W. S., Wang, X. J., Ren, N. Q. (2013). Minimization of excess sludge production by in-situ activated sludge treatment processes — A comprehensive review. *Biotechnology Advances*, **31**, 1386–1396, doi:10.1016/j.biotechadv.2013.06.003.

Henze, M., Grady, C. P. L. Jr., Gujer, W., Marais, G. V. R., Matsuo, T. (1987). Activated sludge model No. 1. IAWQ Scientific and Technical Report No. 1, London, UK.

Henze, M., Gujer, W., Mino, T., Matsuo, T., Wentzel, M. C., Marais, G. V. R., Van Loosdrecht, M. (1999). Activated sludge model No. 2d, *Water Science and Technology*, **39**, 165–182.

Henze, M., van Loosdrecht, M. C. M., Ekama, M. C., Brdjanovic, D. (2008). Biological Wastewater Treatment: Principles, Modelling and Design. London: IWA Publishing.

Hreiz, R., Latifi, M. A., Roche, N. (2015). Optimal design and operation of activated sludge processes: State-of-the-art. *Chemical Engineering Journal*, **281**, 900-920, doi:10.1016/j.cej.2015.06.125.

Jenkins, D. and Orhon, D. (1972). The mechanism and design of the contact stabilization activated sludge process. International Association on Water Pollution Research, Advances in Water Pollution Research, Proceeding.

Khursheed, A., Sharma, M. K., Tyagi, V. K., Khan, A. A., Kazmi, A.A. (2015). Specific oxygen uptake rate gradient – Another possible cause of excess sludge reduction in oxic-settling-anaerobic (OSA) process. *Chemical Engineering Journal*, **281**, 613–622.

Labelle, M. A., Dold, P. L., Comeau, Y. (2015). Mechanisms for reduced excess sludge production in the cannibal process. *Water Environment Research*, **87(8)**, 687-696.

Li, X., Xu, K., Fu, W., Wang, J., Zhu, Y., Li, C., Zhou, X. (2014a). Simultaneous in-situ sludge reduction and removal of organic carbon and nitrogen by a pilot-scale continuous aerobic-anaerobic coupled (CAAC) process for deeply treatment of soybean wastewater. *Biochemical Engineering Journal*, **85**, 30-37, doi:10.1016/j.bej.2014.01.007.

Li, X., Liu, X., Wu, S., Rasool, A., Zuo, J., Li, C., Liu, G. (2014b) Microbial diversity and community distribution in different functional zones of continuous aerobic-anaerobic coupled process for sludge in situ reduction. *Chemical Engineering Journal*, **257**, 74–81, doi:10.1016/j.cej.2014.07.028.

Li, K., Wang, Y., Zhang, Z., Liu, D. (2014c). Effects of oxidation reduction potential in the bypass micro-aerobic sludge zone on sludge reduction for a modified oxic-settling-anaerobic process. *Water Science & Technology*, **69**, 2139-2146, doi:10.2166/wst.2014.135.

Low, E. W., Chase, H. A. (1999). Reducing production of excess biomass during wastewater treatment. *Water Research*, **33(5)**, 1119-1132.

Mahmood, T. and Elliot, A. (2006). A review of secondary sludge reduction technologies for the pulp and paper industry. *Water Research,* **40**, 2093-2112 doi:10.1016/j.watres.2006.04.001.

McCarty, P. L., Brodersen, C. F. (1962). Theory of extended aeration activated sludge. *Journal - Water Pollution Control Federation*, **34**, 1095–1103.

McKinney, R. E. (1956). Biological flocculation, in Biological Treatment of Sewage and Industrial Wastes: Vol. 1, Aerobic Oxidation, ed. By McCabe, J.

and Eckenfelder, Jr W. W. Reinhold Publishing Co, New York, pp. 88–100.

Metcalf and Eddy, Inc. (2003). Wastewater engineering — treatment, disposal and reuse. 3rd Edition. New York, USA: McGraw Hill.

Ning, X., Qiao, W., Zhang, L., Gao, X. (2014). Microbial community in anoxic–oxic–settling–anaerobic sludge reduction process revealed by 454 pyrosequencing analysis. *Canadian Journal of Microbiology*, **60**, 799–809, doi:10.1139/cjm-2014-0263.

Niu, T., Zhou, Z., Shen, X., Qiao, W., Jiang, L., Pan, W., Zhou, J. (2016). Effects of dissolved oxygen on performance and microbial community structure in a micro-aerobic hydrolysis sludge in situ reduction process. *Water Research*, **90**, 369-377, doi:10.1016/j.watres.2015.12.050.

Orhon, D. and Artan, N. (1994). Modelling of Activated Sludge Systems. Lancaster: Technomic Publishing Co.

Orhon, D., Ateş, E., Sözen, S., Çokgör, E. U. (1997). Characterization and COD fractionation of domestic wastewaters. *Environmental Pollution*, **95(2)**, 191-204.

Orhon, D., Okutman, D., Insel, G. (2002). Characterisation and biodegradation of settleable organic matter for domestic wastewater. *Water SA*, **28(3)**, 299-306.

Orhon, D. (2015). Evolution of the activated sludge process: The first 50 years. *Journal of Chemical Technology and Biotechnology*, **90(4)**, 608-640, doi:10.1002/jctb.4565.

Özdemir, S., Çokgör, E. U., İnsel, G., Orhon, D. (2014). Effect of extended aeration on the fate of particulate components in sludge stabilization. *Bioresource Technology*, **174**, 88–94, doi:10.1016/j.biortech.2014.10.002.

Reichert, P., Ruchti, J., Simon, W. (1998). AQUASIM 2.0, Swiss Federal Institute for Environmental Science and Technology (EAWAG), CH-8600, Duebendorf, Switzerland.

Reynolds, T. (1973). Aerobic digestion of thickened waste activated sludge. Proceedings 28th Industrial Waste Conference, Purdue University, Lafayette, Indiana.

Rodriguez-Perez, S. and Fermoso, F. G. (2016). Influence of an oxic settling anoxic system on biomass yield, protozoa and filamentous bacteria. *Bioresource Technology*, **200**, 170–177, doi:10.1016/j.biortech.2015.09.106.

Saby, S., Djafer, M., Chen, G.H. (2003). Effect of low ORP in anoxic sludge zone on excess sludge production in oxic-settling-anoxic activated sludge process. *Water Research*, **37**, 11–20.

Sanin, F. D., Clarkson, W. W., Vesilind, P. A. (2011). Sludge Engineering: The Treatment and Disposal of Wastewater Sludges. DEStech Publications, Inc., Lancaster.

Sarria, N. V., Victoria, J. R., Lozada, P. T., Parra, C. M. (2011). Performance of a contact stabilization process for domestic wastewater treatment of Cali, California. *Dyna*, **168**, 98-107.

Siemens Water Technologies Corporation (2007). Cannibal Solids Reduction Process. Water Technologies. (http://www.siemens.com/about/sustainability/pool/en/environmentalportfolio/productssolutions/water/cannibal_solids_reduction_system.pdf)

Spellman, F. R. (1997). Wastewater biosolids to compost. Lancaster, PA, USA: Technomic Publishing Company.

Sun, L. P., Chen, J. F., Guo, W. Z., Fu, X. P., Tan, J. X., Wang, T. J. (2015). Study of the sludge reduction in an oxic–settling– anaerobic activated sludge process based on UNITANK. *Water Science & Technology*, **71**, 111-116, doi:10.2166/wst.2014.474.

Tas, D. O., Karahan, Ö., Övez, S., Orhon, D., Spanjers, H. (2009). Biodegradability and denitrification potential of settleable chemical oxygen demand in domestic wastewater. *Water Environment Research*, **81(7)**, 715-727.

Tchobanoglous, G., Burton, F. L., Stensel, H. D (2003). Wastewater Engineering (4th edition). USA : McGraw – Hill.

Turovskiy, I., and Mathai, P.K. (2006). Wastewater Sludge Processing Willey and Sons, Inc., New Jersey.

WEF, Water Environment Federation (1987). Anaerobic Digestion. Manual of practice no. 16, 2nd ed., Alexandria, Virginia.

WEF, Water Environment Federation (1995). Wastewater residuals stabilization. Manual of practice FD-9. Alexandria,Virginia.

Wei, Y., Van Houten, R. T., Borger, A. R., Eikelboom, D. H., Fan, Y. (2003). Minimization of excess sludge production for biological wastewater treatment. *Water Research,* **37**, 4453-4467, doi:10.1016/S0043-1354(03)00441-X.

Url-1 < http://envirosim.com/products/biowin >, date retrieved 11.11.2016.

Url-2 < http://www.goldsim.com/Web/Solutions/EnvironmentalSystems/ >, date retrieved 11.11.2016.

Yagci, N., Novak, J. T., Randall, C. W., Orhon, D. (2015). The effect of iron dosing on reducing waste activated sludge in the oxic-settling-anoxic process. *Bioresource Technology*, **193**, 213–218, doi:10.1016/j.biortech.2015.06.109.

Yang, S., Guo, W., Chen, Y., Peng, S., Du, J., Zheng, H., Feng, X., Ren, N. (2016). Simultaneous in-situ sludge reduction and nutrient removal in an A^2MO-M system: Performances, mechanisms, and modeling with an extended ASM2d model. *Water Research*, **88**, 524-537, doi:10.1016/j.watres.2015.09.046.

Ye, F. and Li, Y. (2010). Oxic-settling-anoxic (OSA) process combined with 3,3’,4’,5-tetrachlorosalicylanilide (TCS) to reduce excess sludge production in the activated sludge system. *Biochemical Engineering Journal*, **49**, 229–234.

Zhou, Z., Qiao, W., Xing, C., An, Y., Shen, X., Ren, W., Jiang, L. M., Wang, L. (2015a). Microbial community structure of anoxic–oxic-settling-anaerobic sludge reduction process revealed by 454-pyrosequencing. *Chemical Engineering Journal*, **266**, 249–257, doi:10.1016/j.cej.2014.12.095.

Zhou, Z., Qiao, W., Xing, C., Wang, C., Jiang, L. M., Gu, Y., Wang, L. (2015b). Characterization of dissolved organic matter in the anoxic–oxic-settling-anaerobic sludge reduction process. *Chemical Engineering Journal*, **259**, 357–363, doi:10.1016/j.cej.2014.07.129.

CURRICULUM VITAE

Name Surname : BUŞRA ALLI

Place and Date of Birth : 14/05/1991, ISTANBUL

E-Mail : alli@itu.edu.tr

EDUCATION :

- **B.Sc.** : 2014, Istanbul Technical University, Faculty of Civil Engineering, Environmental Engineering Department

PROFESSIONAL EXPERIENCE:

- 2014-Present, Environmental Engineer, ENVIS Energy and Environmental Systems Research and Development Ltd.

PUBLICATIONS:

- Orhon, D., Sözen, S., Teksoy Basaran, S., Alli, B. (2016). Super fast membrane bioreactor – total waste recycle and reuse with energy conservation. Desalination and Water Treatment, 57(45), 21160-21172.
- Salimi Khaligh, S., Yagci, N., Ubay Cokgor, E., Karaca, C., Alli, B., Orhon, D., Sozen, S. (2016). Biodegradation of pretreated olive mill effluent in mixture with a domestic sewage or compatible wastewater stream. Journal of Chemical Technology and Biotechnology, Accepted for publication.