İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

EVALUATION OF AEROBIC STABILIZATION CHARACTERISTICS FOR BREWING INDUSTRY WASTEWATER TREATMENT SLUDGE

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FOREWORD

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TABLE OF CONTENTS

Page

ABBREVIATIONS

ATV-DVWK : German Association for water management, wastewater and waste
BTEX : Benzene, Toluene, Ethylbenzene, and Xylenes
BOD : Biochemical Oxygen Demand
CAS : Conventional Aerobic Stabilization
COD : Chemical Oxygen Demand
DOC : Dissolved Organic Carbon
DS : Dry Solids
EC : European Commission
EU : European Union
LOI : Loss on Ignition
MLSS : Mixed Liquor Suspended Solids
MLVSS : Mixed Liquor Volatile Suspended Solids
PCB : Polychlorinated Biphenyls
SOUR : Standard Oxygen Uptake Rate
SS : Suspended Solids
TKN : Total Kjeldahl Nitrogen
TP : Total Phosphorus
TOC : Total Organic Carbon
TSS : Total Suspended Solids
UASB : Upflow Anaerobic Sludge Blanket
US EPA : United States Environmental Protection Agency
VS : Volatile Solids
VSS : Volatile Suspended Solids
WEF : Water Environment Federation

LIST OF TABLES

Page

LIST OF FIGURES

Page

EVALUATION OF AEROBIC STABILIZATION CHARACTERISTICS FOR BREWING INDUSTRY WASTEWATER TREATMENT SLUDGE

SUMMARY

In recent years, sludge produced from industrial wastewater treatment plants is becoming to be a larger environmental concern in Turkey. In order to avoid future complications within landfills, it is important for the sludge to be stabilized which is defined as the destruction of the organic content via biochemical oxidation processes. Current national waste management legislation, which has been revised in accord with requirements for accession to European Union, became more stringent and furthermore emphasized the problem of waste sludge. Based on this rationale, current legislation on landfilling classifies unstabilized sludge with high organic content as hazardous waste. Consequently, industries with highly organic sludge, such as brewing industry, face drastically higher waste management costs.

This study presents an introduction including; general overview of industrial wastewater treatment plant sludge management, aim and scope of the study as well as current and near future legal framework related to the subject of the study. In addition, a broad literature survey on two topics is provided; (i) sludge stabilization methods and post-stabilization final disposal routes and (ii) brewery industry waste profile with emphasis on wastewater and sludge characteristics.

Furthermore, this study principally presents a feasible sludge stabilization solution, for brewing industry, which enables final disposal routes such as landfill. As a suitable method, aerobic stabilization is evaluated through a series of laboratory studies investigating stabilization characteristics up to the point where organic content is sufficiently reduced in order to meet current legal requirements. With the intention of estimating aerobic stabilization characteristics for brewing industry wastewater treatment sludge, organic carbon parameters are analyzed for sludge cake. Based on these analyses, landfilling is examined whether it can be a possible final sludge disposal method. Moreover, a connection between organic content of the treated wastewater and organic content of the produced sludge is examined, based on given theoretical relationship.

BİRA ENDÜSTRİSİ ARITMA ÇAMURLARININ AEROBİK STABİLİZASYON ÖZELLİKLERİNİN İNCELENMESİ

ÖZET

Son yıllarda Türkiye'de, endüstriyel atıksu arıtma tesislerinden kaynaklanan çamur giderek daha büyük bir çevre problem olmaktadır. Katı atık düzenli depolama sahalarında karşılaşılabilecek muhtemel sorunların önüne geçmek için çamurun stabil olması yani organik içeriğinin biyokimyasal oksidasyon prosesi ile parçalanmış olması çok önemlidir. Avrupa Birliği uyum yasaları çerçevesinde güncellenen mevcut ulusal mevzuat geçmişe kıyasla daha sıkı koşullar getirmekte ve özellikle arıtma çamurları problemine vurgu yapmaktadır. Bu noktadan hareketle mevcut düzeli depolama mevzuatı organik içeriği yüksek stabil olmayan çamuru tehlikeli atık olarak sınıflandırmaktadır. Bu durumun bir sonucu olarak özellikle bira endüstrisi gibi yüksek organik madde içerikli çamura sahip olan endüstriler çok büyük ölçüde artan atık yönetim maliyetleri ile yüz yüze gelmektedir.

Bu çalışma, endüstriyel atıksu arıtma çamuru yönetiminin genel görünümünü, çalışmanın amaç ve kapsamını aynı zamanda çalışma konusu ile ilgili mevcut ve yakın gelecekte geçerli olacak olan yasal çerçeveyi içeren bir giriş sunmaktadır. İlave olarak, iki başlık üzerinde geniş bir literature taraması sunulmuştur; (i) çamur stabilizasyon yöntemleri ve stabilizasyon sonrası nihai bertaraf yolları ve (ii) özellikle atıksu ve çamur karakterizasyonuna odaklanan bira endüstrisi atık profili.

Ayrıca, bu çalışma bira endüstrisi için fizibıl ve nihai bertaraf yöntemi olarak düzenli depolamayı mümkün kılan bir çamur stabilizasyonu çözümü sunmaktadır. Uygun yöntem olarak aerobik stabilizasyon bir dizi laboratuvar çalışması ile değerlendirilmiş, stabilizasyon özellikleri organik içeriğin yeterince azaltılıp yasal gerekliliklerin sağlanabildiği noktaya kadar incelenmiştir. Bira endüstrisi atıksu arıtma çamurlarının aerobik stabilizasyon karakterinin incelenmesi amacıyla çamur kekinde organik karbon parametreleri analiz edilmiştir. Bu analizlere dayanarak nihai bertaraf için düzenli depolamanın uygulanabilirliği incelenmiştir. Bunun dışında, arıtılan atıksuyun organik madde içeriği ile çamurun organik madde içeriği arasında ki bağlantı deneysel olarak araştırılmış, bu ilişkinin teorik yönü açıklanmıştır.

1. INTRODUCTION

In our country, sludge generated from industrial wastewater treatment plants, causes more environmental problems each day. Completion of stabilization, which means conversion of organic matter content to final products via biochemical oxidation process, is essential in terms of avoiding problems at landfills, where waste sludge is disposed and preventing pollutants in sludge to go back to the water cycle. Waste management legislation, which Turkey updated in accordance with European Union (EU) accession requirements, became more stringent which also emphasized the problem of waste sludge. Current directives on hazardous waste and landfills define sludge as hazardous waste if it has high organic content and it is unstabilized. This condition increases waste disposal costs significantly especially for industries like brewing industry which due to its nature generates sludge with high organic fractions.

1.1 Aim of the Thesis

General aim of the study is to present alternative solutions for brewing industry wastewater treatment sludge disposal. Specific aims can be defined in following points; (i) evaluation of pre-thickened sludges' aerobic stabilization in a separate tank, (ii) investigation of stabilized and dewatered sludges' legal compatibility and landfilling possibility, (iii) investigation of the relation between wastewater parameter chemical oxygen demand (COD) and sludge parameter total organic carbon (TOC), (iv) conceptual design and cost analysis of aerobic stabilization tank in case of successful sludge lab analysis results.

1.2 Scope of the Thesis

With respect to the aim of the thesis, necessary data and samples have been collected from a case study brewery wastewater treatment plant. Further wastewater and sludge characterization studies have been carried out.

Series of laboratory studies have been completed focusing on aerobic stabilization of brewery wastewater treatment sludge. In order to exclude sludge from hazardous waste class, necessary solution suggestions have been introduced, aiming to reduce TOC and DOC (dissolved organic carbon) values and meet desired standards. In order to evaluate aerobic stabilization characteristics for brewing industry wastewater treatment sludge, other than TOC and DOC parameters, SS (suspended solids), VSS (volatile suspended solids) and COD analysis have been carried out.

1.3 Legal Framework

In Turkey national legislation, regarding sludge management mainly follows EU sludge legislation, which consists of European Commission (EC) directives. For the subjects of sludge management (treatment, disposal etc.) Ministry of Environment and Forestry (MoEF) prepares and enforces national legislation. National legislation on sludge includes several regulations and communiqué such as (i) Regulation on Urban Wastewater Treatment, (ii) Regulation on the Control of Solid Waste, (iii) Regulation on the Control of Hazardous Waste, (iv) Regulation on the Control of Soil Pollution, (v) Regulation on the General Basis of Waste Management and (vi) Draft Regulation on the Landfilling of Waste.

Regulation on Urban Wastewater Treatment (Date: 08/01/2006 and No: 26047) defines the ban on disposal of sludge into receiving water bodies in Article 5 (f) and also Article 5 (g) declares sludge can be reused under proper conditions, reuse as soil amender is regulated under Regulation on the Control of Soil Pollution.

Regulation on the Control of Solid Waste (Date: 14/03/1991 and No: 20814) requires a maximum of 65% water content in sludge to be disposed in a landfill however landfill operators do have the option of accepting sludge with higher water content (up to 75%) if it is determined that stability and odor problems will not arise at landfill.

Regulation on the Control of Hazardous Waste (Date: 14/03/2005 and No: 25755) includes Annex-11A which provides landfilling criteria for waste by dividing waste into three categories (inert waste, non-hazardous waste and hazardous waste) according to two groups of parameters. First group named as eluent criteria consists of 18 different parameters, which include heavy metals, chloride, fluoride, sulfate, dissolved organic carbon, total soluble solids and phenol index. Second group named original waste criteria consists of 5 different parameters, which include total organic carbon, BTEX, PCBs, mineral oil and loss on ignition (LOI). Wastes with eluent concentrations within range of hazardous waste, are regulated to be disposed at hazardous waste landfills. Wastes with eluent concentrations within range of non-hazardous waste, are regulated to be disposed in mono-type (separate) at municipal solid waste landfill sites. Wastes with eluent concentrations below values of inert hazardous waste, are regulated to be disposed with municipal solid waste at landfills.

Regulation on the Control of Hazardous Waste Annex-11A is based on several parameters. Even though, studies related to domestic wastewater treatment plants and industrial wastewater treatment plants which treat high organic loads, such as brewing industry, indicate that most of the sludges have a TOC and/or DOC (Table 1.1) value which classifies sludge as hazardous and therefore, makes the landfill disposal of the sludge not viable (Pehlivanoglu-Mantas et al., 2007). In respect to interpretation of analysis results, directive indicates that eluent concentrations will be given a priority for classification of waste as hazardous, non-hazardous or inert and waste will be landfilled according to its class.

Table 1.1: Landfill criteria for waste

Parameters (units, types)	Inert waste limits	Non-hazardous waste limits	Hazardous waste limits
DOC (mg/L, eluent* criteria)	≤50	50-80	80-100
TOC (mg/kg, original waste criteria)	≤30,000	50,000	60,000

*Liquid/Solid (L/S) ratio = 10 L/kg

Regulation on the Control of Soil Pollution (Date: 31/05/2005 and No: 25831) includes legal aspects for land application of sludge and compost. Regulation indicates that sludge, from treatment plants that treat domestic wastewater or industrial wastewater with domestic characteristics, can be used as soil amender (conditioner) only after sludge is stabilized, land application of raw sludge is prohibited. Article 13 of this regulation defines limitations and inhibitions for stabilized sludge land application which include heavy metals limit values for stabilized sludge (Annex I-B) and heavy metals limit values for soil (Annex I-A(a)) which sludge will be applied to. In addition, same article bans sludge to be applied to vegetable and fruit products (excluding fruit trees), which are grown in contact with soil and freshly consumed. Furthermore, it is prohibited to apply sludge on soils within watershed protection zones and soils with a pH value less than 5.

Regulation on the General Basis of Waste Management (Date: 05/07/2008 and No: 26927) presents waste list including waste codes and markings. Waste codes are used to identify sources of waste and markings are used to identify hazardous waste. For example, marking (A) means absolute entry which indicates that waste is directly classified as hazardous waste where as marking (M) means mirror entry which indicates that waste's hazardous property must be assessed in accordance with Annex-III A (hazard properties) and Annex-III B (hazard threshold concentrations). Sludge produced from brewing industry wastewater treatment is defined under code 02 07 05 with no marking, which indicates that waste is non-hazardous. However, if landfilling is the chosen disposal route for sludge than classification of hazardous waste and suitability for landfill are determined by a different procedure in accordance with Regulation on the Control of Hazardous Waste.

Draft Regulation on the Landfilling of Waste, outlines waste acceptance criteria for landfills. When gained formality in future, this regulation will replace landfill waste acceptance criteria in previous hazardous waste directive. In both of these regulations, TOC and DOC limits, for all types of landfills (inert, non-hazardous and hazardous), are the same however only in draft regulation it's included that, after certain considerations, limit values for TOC could be doubled for inert waste landfills and tripled for non-hazardous waste landfills. No such increase is available for DOC limits.

2. SLUDGE STABILIZATION

2.1 Definition

The most important process goals of sludge stabilization are presented by ATV-DVWK (2003); as the primary goal (i) the stabilization of the organic content, as secondary goals (ii) the reduction of pathogens, (iii) the elimination of offensive odors, (iv) the improvement of the dewatering characteristics of the sludge, (v) the reduction of sludge quantity, (vi) the utilization of biogas (with anaerobic stabilization only). The main objective of this study is to evaluate reduction of organic content in brewery wastewater treatment sludge; therefore, the stabilization process is used within that scope.

Stabilization is not practiced at all wastewater treatment plants, but it is used by a vast majority of plants ranging in size from small to very large.

2.2 Types

In a general overview, types of stabilization processes can be classified under three main categories as follows; (i) biological stabilization, (ii) chemical stabilization and (iii) thermal drying. As described in previous topic, the main aim of this study is to analyze decrease in volatile (organic) fraction of the sludge, which can only be accomplished through biological stabilization.

Chemical stabilization also known as lime or alkaline stabilization uses addition of lime to untreated sludge in sufficient quantity to raise the pH to 12 or higher (Tchobanoglous et al., 2003). The high pH creates an environment that halts microbial reactions. The sludge will not putrefy, create odors and virus, bacteria and other microorganisms will remain inactivated. Although, chemical stabilization reduces odor production and pathogen activity, this method is not applicable to reduce organic content of sludge.

Thermal drying involves the application of heat to evaporate water. As Vesilind (2003) indicates, thermal drying increases the solids content to a level above that achievable by usual mechanical dewatering (% 30-90 dry solids-DS). The primary objectives of thermal drying is to reduce the quantity of solids as well as pathogen reduction but in a similar fashion to chemical stabilization, thermal drying is also not valid for decreasing organic fraction of sludge. Incineration can also be explained as ultimate stabilization but incineration represents the final step in a sludge management cycle, therefore it is considered a final disposal method rather than a treatment-stabilization method.

Due to reasons provided above, this study only focuses on biological stabilization as a tool to minimize organic content of sludge. The principal methods used for biological stabilization of sludge are:

(1) Extended aeration
(2) Composting
(3) Anaerobic stabilization
(4) Aerobic stabilization

2.2.1 Extended aeration

Sludge stabilization in extended aeration processes takes place in the aeration tank, simultaneously with the oxidation of the influent organic matter process, because the food/microorganism (F/M) ratio is low. Tchobanoglous et al. (2003) states that main advantages of extended aeration process are:

- relatively simple design and operation
- low biosolids production rate
- well stabilized sludge

Main disadvantages associated with the process are:

- high energy use
- relatively large aeration tanks
- not easy to adapt an old plant

Extended aeration activated sludge systems need SRTs higher than 20 days and up to 40 days according to Tchobanoglous et al. (2003) and ATV-DVWK (2000) indicates that the sludge age is to be selected in accordance with the relevant wastewater temperature. Design criteria for extended aeration systems are presented in Table 2.1 (Tchobanoglous et al., 2003).

Table 2.1: Typical design parameters for extended aeration process

Parameters (Units)	SRT (days)	F/M (kg BOD/kg MLVSS·d)	Volumetric loading (kg BOD/m^3·d)	MLSS (mg/L)	HRT (hours)
Typical values	20-40	0.04-0.10	0.1-0.3	2000-5000	20-30

2.2.2 Composting

This section explains general theory (including advantages and disadvantages) of composting, composting systems and associated typical operations as well as process control, operational issues are not discussed.

2.2.3.1 General theory

Composting is a method based on the biological breakdown of organic materials. Composting is one of the typical stabilization processes and is most frequently used to stabilize raw sludge; however, applications for further stabilizing digested sludge are also typical. Most solids composted are used for soil conditioning or horticultural application, appropriateness for use as a soil amendment is defined in accordance to concentrations of certain metals and organic pollutants.

According to WEF (2008), the four principal objectives of composting are:

- biological conversion of organics to a stabilized state
- pathogen destruction
- reduction of sludge quantity (via moisture and volatile solids reduction even though use of bulking agent can add to quantity and overall amount may increase)
- production of a utilizable end product

Composting may progress within either aerobic or anaerobic environments. Most composting operations seek to maintain aerobic conditions throughout the compost mass. Aerobic conditions accelerate material decomposition and result in the temperatures necessary for pathogen destruction. Anaerobic conditions can produce significant foul odors that are not generated when aerobic conditions are maintained throughout the compost mass. The time period required to stabilize the organic material is divided between an active composting stage and a curing stage. Aerated composting necessitates 20 days of aeration usually tracked by 30 days of unaerated curing.

The main advantages of the composting process are (Andreoli et al., 2007):

- high-quality final product, widely accepted in farming
- possible combined use with other stabilization processes
- low capital cost (traditional composting)

The main disadvantages are:

- need for a sludge with high-solids concentration (>35%)
- high operational costs
- need for turning-over and/or air-generation equipments
- considerable land requirements
- odor generating risk

Nonreactor and reactor systems:

Composting can be achieved by reactor or nonreactor systems. Nonreactor (open) systems include the windrow system and the aerated static pile. In the windrow system, aerobic conditions are maintained through convective airflow and periodic turning. Through several turnings or mixings, the sludge is subjected to the higher interior temperatures for pathogen reduction and stabilization of the organic material. Blowers connected to pipes located in the base of the piles either blow or pull air through the compost pile, in the static pile system.

In a reactor-type (mechanical) composting system, the sludge and the bulking agent are mixed and then aerated in silos, rotating drums or horizontal beds. Oxygen concentration and the temperature regime are regulated by synchronized aeration.

2.2.3.2 Typical operations

Although composting systems may be different in form, they all contain the following basic steps:

- mixing of the sludge and bulking agent
- composting or microbial decomposition of the organic matter
- recovery of the bulking agent or product recycling

- curing
- storage
- final disposition of the composted material

Figure 2.1 shows a typical flow diagram for a composting process.

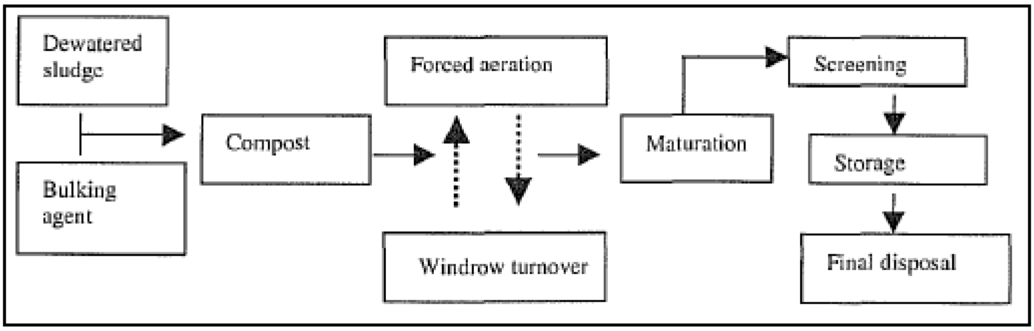

Figure 2.1 Flow diagram of a composting process

Aeration systems:

Aeration systems can be either movable or fixed. Movable aeration equipment includes compost mixers and permanent systems contain blowers that are joined to a pipe or plenum that is put within the compost pile; or, as in a closed reactor system, the pipe or plenum feeds a reactor vessel.

Mixing systems:

An efficient mixing of sludge and bulking agent is vital for swift and even composting. A uniform mix reduces the likelihood of anaerobic pockets within the compost mass, thereby declining the potential for odor creation. Two characteristically used mixing systems are:

- stationary system (plug mill or rotary drum) using paddles to stir the materials
- moving equipment, such as a wheel loader or composter.

Screening:

In the manufacture of a homogeneous fine-grained product and in the revival of the bulking agent for reuse, screening is essential. Trommel, harp, and vibratory screens have been used successfully; however, vibratory screens may be better able to handle wet compost. In order to decrease the moisture content for effective screening, a step of drying can on occasion be incorporated previous to screening.

2.2.3.3 Process control

Moisture, temperature, nutrients, bulking agents, and aeration significantly influence stabilization by composting and are explained under this topic.

Moisture:

Moisture changes the speed of biological activity. At less than approximately 40% moisture, activity begins to decrease. At approximately 60% moisture, the air pore space is blocked. This has an effect on the aeration effectiveness of the system and forms anaerobic zones within the compost bed.

Temperature:

Microbial population is considerably influenced by temperature. Decomposition is fastest in the thermophilic range. Research indicates the optimum temperature to be between 55 and 60 °C; at temperatures more than 60 °C microbial activity decreases (WEF, 2008). One technique to sustain the temperature within the optimal values is to employ forced ventilation or aeration and manage the blower rate in order to keep the pile outflow temperature less than 60 °C.

Nutrients:

Key nutrients that affect composting are carbon and nitrogen. The carbon:nitrogen ratio (C:N) affects the microbial activity and the rate of organic matter decomposition. Microorganisms require carbon for both metabolism and growth, and nitrogen for protein synthesis and cell construction. As WEF indicates, preserving the C:N ratio between 26 and 31 units of carbon per 1 unit of nitrogen, is a good practice that tolerates optimum microbial growth (2008).

Bulking agents:

With the addition of bulking agents to the sludge, several benefits occur such as; moisture control, increase in air voids for proper aeration by providing porosity, formation of structural support for the compost accumulation and organic amendment for C:N ratio adjustment. Important bulking agent properties consist of moisture content, particle size and absorbency.

Aeration:

Aeration is significant for supplying oxygen for the decomposition process, temperature control and moisture reduction. Higher temperatures are achieved under aerobic conditions than under anaerobic conditions. Studies carried out by WEF (2008) suggest that 20 to 50 m^3/h per dry ton of sludge results in oxygen levels from 5 to 15% throughout the pile. At oxygen levels below 5%, anaerobic conditions can occur, resulting in anaerobic zones in the sludge mass, the generation of odors, and inadequate stabilization. Aeration also provides a means of removing moisture and drying the compost product. Extreme moisture can unfavorably influence the equipment handling and processing operation.

2.2.3 Anaerobic stabilization

This section explains general theory (including advantages and disadvantages) of anaerobic stabilization, conventional and advanced anaerobic stabilization processes as well as units and equipments used for anaerobic stabilization, operational issues are not discussed.

2.2.3.1 General theory

Anaerobic stabilization is a multiphase biochemical process that can stabilize various different types of organic material. The word digestion is applied to the stabilization of the organic matter through the activity of bacteria in relation to the sludge, in conditions that are constructive for their growth and reproduction, therefore this study uses the word stabilization instead of digestion whereas the term digester is sometimes used as stabilization unit.

Anaerobic stabilization can be explained in a three-stage system using hydrolysis, acidification/acetogenesis and methanogenesis (ATV-DVWK, 2003). At first stage, extracellular enzymes break down solid complex organic compounds, cellulose, proteins, lignins and lipids into soluble organic fatty acids, alcohols, carbon dioxide and ammonia. At the second stage, acetogenic bacteria convert the products of the first stage into acetic acid, propionic acid, hydrogen, carbon dioxide and other organic acids. At the third stage, two sets of methane-forming bacteria functions; one set to convert hydrogen and carbon dioxide to methane and the other set to convert acetate to methane and bicarbonate. The digesters are preserved excluding oxygen from the process, which is done for the both sets of bacteria that are anaerobic. The three stages are schematically reviewed in Figure 2.2.

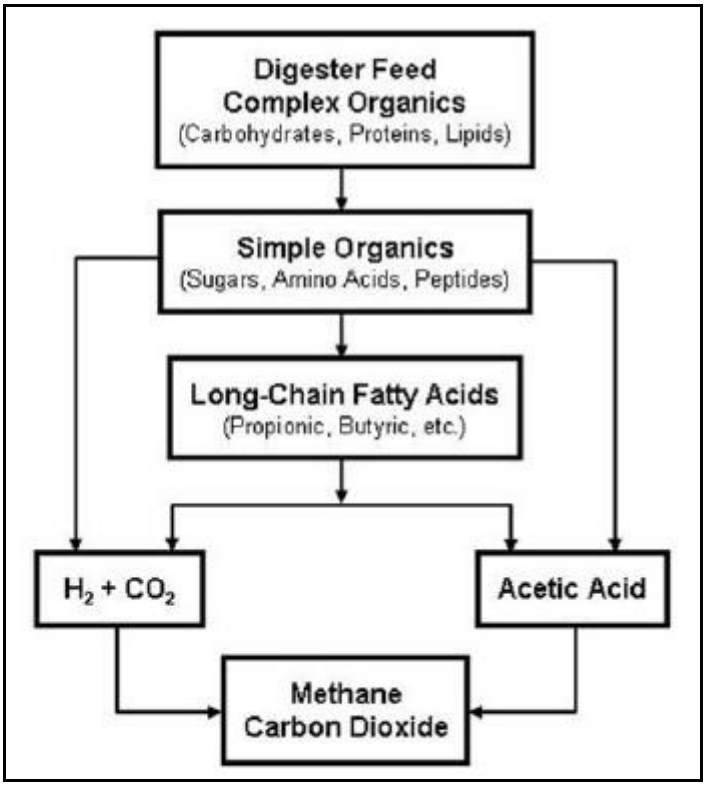

Figure 2.2: Stages of anaerobic stabilization

Methane-forming bacteria control the process in general. Methane bacteria are very receptive to environmental factors and are hard to produce. As a result, process design and the operation of conventional anaerobic stabilization are modified to assure the requirements of the methane-formers.

2.2.3.2 Conventional mesophilic anaerobic stabilization

The mainstream of anaerobic stabilization systems presently in operation are constructed as conventional mesophilic digesters. In these systems, all stages of the biochemical process occur in the same tank and are operated at mesophilic temperatures (32 to 38^{o}C). Conventional systems can be categorized as low-rate (no mixing) or high-rate processes, which include mixing and heating (WEF, 2008). The heating and mixing used in the high-rate processes produce uniform conditions throughout the tank, which results in shorter detention time and more stable conditions than low-rate processes. Thus, the majority of municipal stabilization systems employ the high-rate process (Figure 2.3).

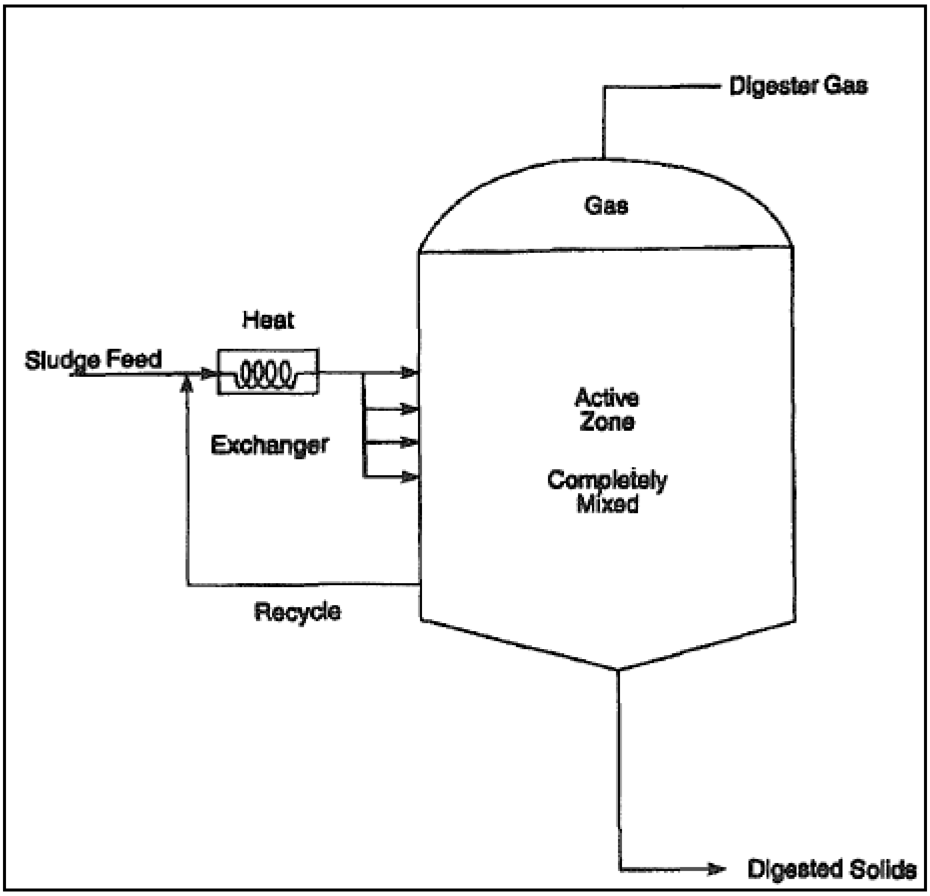

Figure 2.3: High-rate anaerobic stabilization

Of the many environmental issues that affect anaerobic stabilization reaction rates, the most essential are solids retention time, effectiveness of mixing, temperature and pH, these factors are all explained under related topics. Anaerobic stabilization may successfully occur in pH 6-8, although pH is kept nearly neutral in practice, due to buffering capacities of bicarbonates, sulphides and ammonia. Andreoli et al. (2007) states that, for anaerobic process the optimum pH is 7.0. Adapted from Andreoli Table 2.2 presents general design criteria for anaerobic stabilization process.

Table 2.2: Typical design parameters for anaerobic stabilization process

Parameters (Units)	Typical values
SRT (days)	18-25
Volumetric loading (kg VSS/m^3·d)	0.8-1.6
Total solids volumetric loading (kg SS/m^3·d)	1.0-2.0
Influent sludge solids concentration (%DS)	3-8
Volatile suspended solids reduction (%VSS)	40-55
Gas production (m^3/kg VSS reduced)	0.8-1.1

Anaerobic stabilization digests solids by decreasing the mass of volatile solids typically by 40 to 50%. Digesters are sized to provide sufficient detention time to allow stabilization. High-rate digesters are typically sized for an average solids retention time (SRT) of 15 to 20 days (WEF, 2008). Slightly shorter detention times (12 days) are often used in European designs. Anaerobic stabilization is typically used for feed sledge with total solids concentrations of 3 to 5%. On the other hand, it has also been operated on inflow concentrations of 7 to 8% solids at some facilities, generally in Europe.

Anaerobic systems may be judged as useful for stabilization when the volatile solids concentration is 50% or higher and if no biologically inhibitory material are present or probable. Major advantages of anaerobic stabilization defined by Vesilind (2003) are as follows:

- energy (more than that required by the process) is generated
- stabilization of primary solids results in better solids-liquid separation characteristics

Major disadvantages of anaerobic stabilization can be explained as:

- easily upset by unusual conditions or high loadings and is slow to recover
- requires close operational control
- large reactors are required because of the slow growth of methanogens and required solids retention times increasing capital costs
- high organic and nutrient loadings in side streams

2.2.3.3 Advanced anaerobic stabilization processes

Advanced stabilization processes engage adaptation to the conventional stabilization design to attain complete stabilization, advance pathogen reduction and improve digester operation. Two types of advanced anaerobic stabilization processes are explained as follows; acid/gas and thermophilic.

Acid/gas stabilization, or two-phase stabilization, is carried out in a two-reactor system to provide separate environments for the acid-forming and methane-forming bacteria so each can be optimized for the specific process.

As a second type of advanced anaerobic stabilization process, thermophilic stabilization processes include one or more stages that are operated at thermophilic temperatures (55^{o}C or higher). The main goal of thermophilic treatment is to achieve greater pathogen destruction; however it can also increase volatile solids destruction and decrease required detention times. Also some multistage stabilization processes are available, which includes various combinations of mesophilic and thermophilic treatment. Temperature phased anaerobic stabilization includes at least one thermophilic stage followed by a mesophilic polishing stage.

2.2.3.4 Pre-treatment processes for anaerobic stabilization

Pre-treatment is an addition to conventional anaerobic stabilization, aiming to improve; digester performance, volatile solids reduction, gas production and pathogen destruction and to decrease foaming potential. WEF (2008) states that pre-treatment typically include application of energy in the form of ultrasound, heat, pressure or a combination of these. Ultrasound treatment, thermal hydrolysis, pasteurization and homogenization are some cases of pretreatment appliances.

2.2.3.5 Anaerobic stabilization units and equipment

Anaerobic stabilization units can be constructed using a selection of tank and equipment types.

Tank types:

The most widespread type of digester presently applied (especially North America) is the cylindrical tank. According to WEF (2008), cylindrical tanks typically have cone-shaped floors, with slopes of 1:4 to 1:6 to facilitate collection and removal of heavy sludge and grit. Cylindrical tanks, which are usually made of of concrete, can be equipped with gas-holder covers to supply storage for produced gas.

Egg-shaped digesters are designed providing steeper bottom slopes than the cylindrical tanks (typically, slopes that are at least 1:1). They may be constructed of concrete or steel and are available in several variations. Egg-shaped digesters includes common features include a conical bottom and a domed top, they pose advantages including a reduced potential for grit accumulation because of their steep bottom slopes, a geometry that allows for more efficient mixing and thus reduces energy use and less potential for scum accumulation due to the small liquid surface area at the top of the egg-shaped tank (Tchobanoglous et al., 2003). Lacking of capacity for gas storage inside the tank and a shape that is a bit more complicated to insulate are the main disadvantages.

Secondary digesters:

The majority of medium-to-large anaerobic stabilization units consist of both primary and secondary digesters. Most of the stabilization and gas production occurs in the primary digester. While primary digesters are mixed and heated to optimize stabilization and meet pathogen-reduction requirements, secondary digesters may or may not be mixed and heated. A secondary digester which is not heated may provide the following benefits: storage for stabilized solids, standby primary tank and supply of seed sludge. Two-stage system can be seen in Figure 2.4.

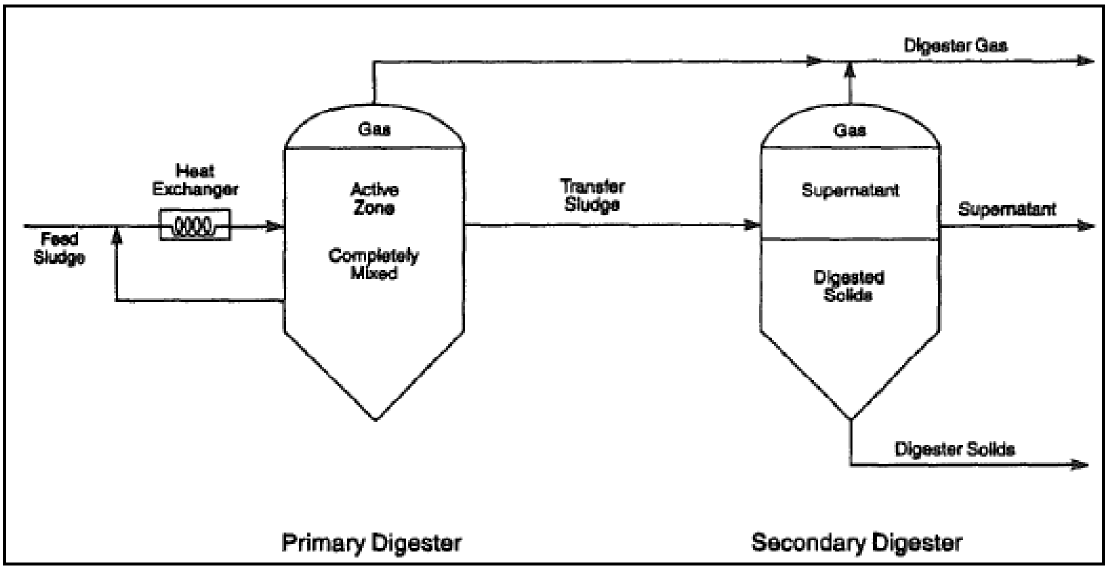

Figure 2.4: Two-stage, high-rate anaerobic stabilization

Digester covers:

Digester covers maintain an oxygen-free environment inside the digester. Covers also prevent digester gas and odors from escaping to the atmosphere, reduce the explosion hazard associated with the methane in the digester gas, and insulate the top of the digester. Four main styles of digester covers are fixed, floating, gas holder, and membrane covers.

Digester mixing:

For high-rate digesters, mixing along with heating, thickening and consistent feeding of influent sludge, is practiced to supply optimal environmental circumstances for the microorganisms that carry out anaerobic stabilization. Effective mixing provides the following benefits; process stability, scum and foam control, and prevention of solids deposition. Types of mixing systems available for digesters include mechanical (impeller, draft tube, pumped recirculation etc.) and gas mixing systems. Digester mixing equipment manufacturers can recommend suitable type, size and power intensity of mixing equipment based on the digester geometry and volume (Vesilind, 2003).

Digester heating:

Methane-forming microorganisms have an optimum growth temperature. If the temperature fluctuations are too wide, methane formers cannot develop the large, stable population needed for the stabilization process. Anaerobic stabilization virtually ceases at temperatures below 10 °C. According to survey done by WEF (2008), most digesters operate in the mesophilic temperature range 32 to 38 °C, while some operate in the thermophilic range 55 to 60 °C. Digester contents' temperature should not vary by more than 0.6 °C per day, apart from the operating temperature.

An interior heating system conveys heat to solids in the stabilization tank. Early internal heating arrangements consisted of pipes mounted to the interior face of the digester walls, and mixing tubes equipped with hot water jackets. These systems have lost popularity because much of the heating equipment and piping is inaccessible for inspection or service, unless the tank is dewatered. In external heating systems, solids are recirculated through an external heat exchanger. Tube-in-tube, tube-in-bath, and spiral-plate exchangers are typical types of external heat providing equipment.

Chemicals feeding:

Due to the changing quality and quantity of the inflow, chemical feed systems occasionally become essential. Changes in alkalinity, pH, sulfides, or heavy metal concentrations may necessitate incorporating chemical addition into the total process. At some point in the early design phase, feeding systems for chemicals (sodium bicarbonate, ferrous chloride, ferrous sulfate, lime, and alum) should be considered.

Gas handling and utilization:

Digester gas, also known as biogas, is produced during the final phase of anaerobic stabilization, when microorganisms change organic acids and carbon dioxide to methane and water. Gas production is directly related to the quantity of volatile solids destroyed by stabilization. Typical values range from 0.75 to 1.1 m^3/kg of volatile solids destroyed (WEF, 2008). The biogas generated in the anaerobic stabilization process is composed primarily of methane (60 to 65%) and carbon dioxide (35 to 40%). Digester gas is a valuable resource that can be used to meet a treatment plant's energy requirements. However, the gas must be treated to remove contaminants (mainly moisture and hydrogen sulfide) that would otherwise damage equipment fueled by the gas and shorten its useful life. Also, many designs are provided with sediment traps and foam separators for biogas cleaning.

Digester gas is a important energy source that has conventionally been used to heat boilers to generate steam or hot water for process and building heating and/or to drive combustion turbines or engine generators to produce electric power (and hot water from heat recovery for heating) or to run dryer units to eliminate moisture from the solids (with heat recovery to heat digesters).

2.2.4 Aerobic stabilization

This section provide an introduction to aerobic stabilization and explains its general theory (including advantages and disadvantages), conventional and other types of aerobic stabilization processes, units and equipments used for aerobic stabilization as well as operational issues.

2.2.4.1 Introduction to aerobic stabilization

Aerobic digestion is a biological treatment process that employs long-term aeration to stabilize and decrease the total mass of organic waste by biologically reducing volatile solids. The word digestion is applied to the stabilization of the organic matter through the activity of bacteria in relation to the sludge, in conditions that are constructive for their growth and reproduction, therefore this study uses the word stabilization instead of digestion whereas the term digester is sometimes used as stabilization unit. This process expands decay of solids and re-growth of organisms to a level where available energy in active cells and storage of waste materials are adequately low to allow the waste sludge to be regarded as stable for land application or other disposal techniques.

Aerobic stabilization has been used for several decades to stabilize the waste solids produced at municipal and industrial wastewater treatment plants. Its popularity, mainly in US and Germany, increased throughout the 1960s and into the 1970s because of its simplicity and lower capital cost relative to anaerobic stabilization

(Grady et al., 1999). Although it had previously been used primarily in small wastewater treatment plants, during this period it was also used in medium to large facilities. This trend was halted in the mid 1970s as rapidly escalating energy costs adversely impacted its overall cost-effectiveness relative to other solids stabilization options. Then, regulations for the management of solids were brought, requiring control of pathogens when solids are to be reused and this additionally reduced the usefulness of aerobic stabilization since its rates of pathogen destruction are usually poorer than anaerobic stabilization.

Characteristically, if a primary settling process was included into the plant, anaerobic stabilization was the process of choice because dependable methods to thicken and aerobically stabilize higher than 3% solids were not developed at the time. Solids concentrations higher than 3% in conventional digesters jeopardize the oxygen transfer efficiency of the system (Andreoli et al., 2007). Because of tighter effluent standards on both nitrogen and phosphorus recently, primary settling tanks were slowly eliminated from the process trains. This was typically done to preserve a good carbon to nitrogen ratio (6:1 recommended), which is normally required to achieve successful biological nitrogen removal. As result of the mixture of the new effluent limits and practices, which presented the ability to control aerobic stabilization processes and precisely forecast the performance of the system, aerobic stabilization has become attractive yet again.

Aerobic stabilization may be used to treat (i) waste activated sludge (WAS) only, (ii) mixtures of WAS or trickling filter sludge and primary sludge, (iii) waste sludge from extended aeration plants, or (iv) waste sludge from membrane bioreactors (MBRs). Aerobic stabilization treats solids that are mostly a result of growth of the biological mass during the treatment process. The aerobic stabilization process renders the digested sludge less likely to generate odors during disposal and reduces bacteriological hazards.

Procedures that enhanced the process performance of aerobic stabilization can be classified under the following categories: (i) pre-thickening, (ii) staged operation and (iii) aerobic-anoxic operation. These techniques and their benefits are summarized by WEF (2008) in Table 2.3.

Table 2.3: Effects of techniques on aerobic stabilization performance

Technique	Improvements
Pre-thickening	Increases SRT Reduces volume requirements Increases volatile solids reduction Increases temperature
Staged operation	Improves digestion and pathogen reduction Reduces volume requirement Reduces oxygen requirement
Aerobic-anoxic operation	Recovers alkalinity and controls pH Provides nitrogen removal Reduces oxygen requirement

According to Vesilind (2003), major advantages of the aerobic process compared with anaerobic process are:

- production of an odorless, biologically stable product
- lower capital costs
- relatively easy operational control with volatile solids reduction slightly less than those achieved in the anaerobic stabilization process
- safer operation with no potential for gas explosion
- discharge of a supernatant with less COD concentrations
- suitability for digesting biosolids rich in nutrient
- less sensitive to upsets and less vulnerable to toxicity

Major disadvantages attributed to the aerobic stabilization process are:

- higher power cost related with oxygen transfer
- decreased efficiency of the process during cold weather
- failure to produce a useful byproduct, such as methane gas
- poorer results achieved during mechanical dewatering

Aerobic stabilization was extensively used to stabilize waste solids from municipal and industrial wastewater treatment plants (WWTPs) because of their comparatively simple operation, low equipment cost and low safety concerns. In the past, the disadvantages associated included high energy costs, reduced exothermic-biological energy during cold weather, alkalinity depletion, poor pathogen reduction, poor volatile solids reduction, and poor standard oxygen uptake rates (SOURs). As an outcome of these performance troubles, prior efforts to use aerobic stabilization as an answer to solids disposal and handling regulations led to comparatively long solids retention time (SRT) values, which increased both the capital and operating costs.

A number of anaerobic digesters have been transformed to aerobic digesters because of the relative easy operation and lower equipment cost and because they can create a improved quality supernatant with both lower nitrates and phosphorus, in this manner protecting the liquid side upstream. Additional benefits of aerobic stabilization are: achieving comparable volatile solids reduction with shorter retention periods, less hazardous cleaning-repairing tasks and an explosive digester gas is not produced, although the gases produced cannot be used for fuel combustion as in anaerobic stabilization. Aerobic stabilization has been used mainly in plants of a size less than 20,000 m^3/d, while, above this size, anaerobic stabilization was normally the selected process.

2.2.4.2 General theory

Aerobic and facultative microorganisms utilize oxygen and attain energy from the available biodegradable organic matter in the sludge during aerobic stabilization. However, when the available food supply in the waste sludge is inadequate, the microorganisms begin to consume their own protoplasm to obtain energy for cell maintenance reactions. Eventually, the cells will undergo lysis, which will release degradable organic matter for use by other microorganisms. The end products of aerobic stabilization typically are carbon dioxide, water, and non-degradable materials (i.e., polysaccharides, hemicelluloses, and cellulose). The term $C_5H_7O_2N$ is the classic formula for biomass or cellular material in an activated sludge system, Tchobanoglous et al. (2003) describes the biochemical changes in an aerobic digester by the following equations:

$C_5H_7O_2N + 5O_2 \rightarrow 4CO_2 + H_2O + NH_4HCO_3$ (destruction of biomass in aerobic stabilization) **(2.1)**

$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O$ (nitrification of ammonia-nitrogen) **(2.2)**

$C_5H_7O_2N + 7O_2 \rightarrow 5CO_2 + 3H_2O + HNO_3$ (complete nitrification) **(2.3)**

$2C_5H_7O_2N + 12O_2 \rightarrow 10CO_2 + 5H_2O + NH_4^+ + NO_3^-$ (with partial nitrification) **(2.4)**

$C_5H_7O_2N + 4NO_3^- + H_2O \rightarrow NH_4^+ + 5HCO_3^- + 2N_2$ (denitrification) **(2.5)**

$2C_5H_7O_2N + 11.5O_2 \rightarrow 10CO_2 + 2N_2 + 7H_2O$ (with complete nitrification and denitrification) **(2.6)**

The cellular material is oxidized aerobically to carbon dioxide, water, and ammonia. Only approximately 75 to 80% of the cell material can be oxidized; the remaining amount is composed of inert components and organic compounds that are not biodegradable. Figure 2.5, based on the traditional decay model for biomass destruction and shows steps for aerobic stabilization.

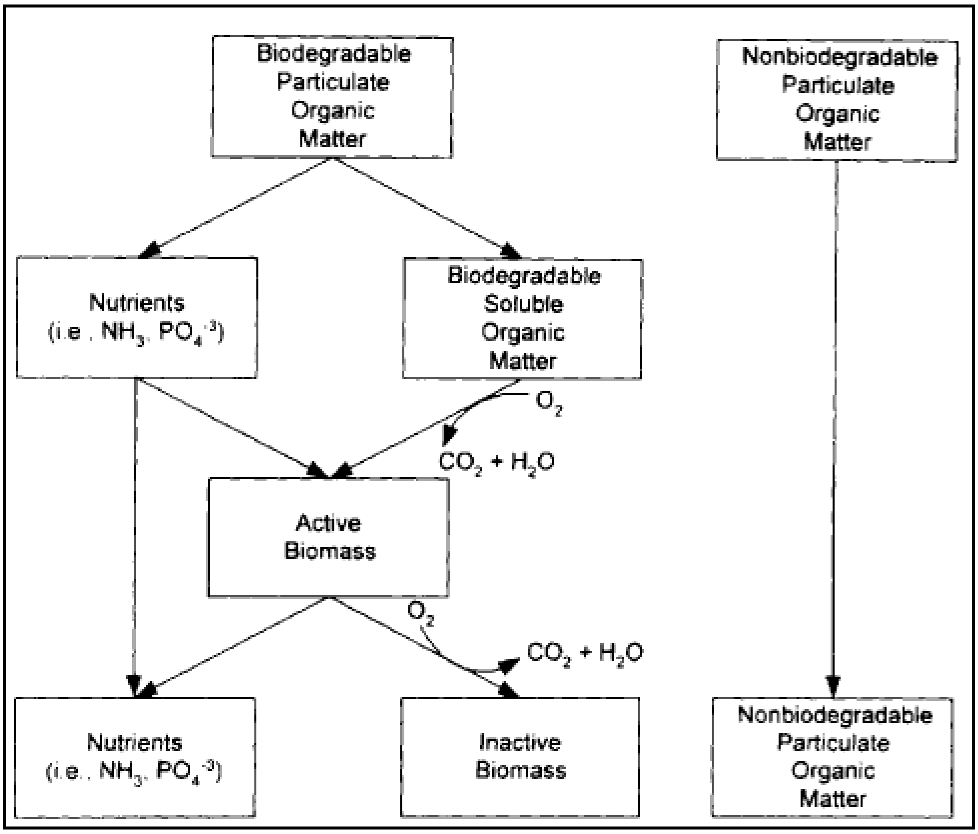

Figure 2.5: Schematic diagram of the aerobic stabilization stages

Grady et al. (1999) indicates that observations of aerobic stabilization processes provide the following conceptual/modeling framework:

- the suspended solids in the influent stream can be segregated into biodegradable and non-biodegradable components. The biodegradable components include particulate organic matter and active biomass, both heterotrophic and autotrophic. The non-biodegradable component consists of particulate inert organic matter and biomass debris (microbial products).

- a non-biodegradable residue will result from aerobic stabilization, even if no non-biodegradable particulate matter is present in the influent solids stream because biomass debris results from the decay of active biomass.

- aerobic stabilization results in the destruction of both volatile suspended solids (VSS) and fixed suspended solids (FSS). This occurs because both the organic and inorganic materials in the biodegradable suspended solids are solubilized and/or oxidized as the solids are digested. However, the volatile and fixed components of the biodegradable and non-biodegradable suspended solids are not equal. Consequently, VSS and FSS will not generally be destroyed in the same proportion. However, in spite of the loss of fixed solids during aerobic stabilization, this study will focus on loss of VSS.

- the biodegradable fraction of solids is a function of their source (primary/secondary sludge or short/long SRT).

- the destruction of biodegradable suspended solids can be characterized as a first order reaction. This occurs because the decay of active biomass is a first order reaction. Biodegradable particulate organic matter is rapidly converted to active biomass. Then that biomass, as well as any active biomass present in the influent, decays in a first order manner, resulting in an overall first order reaction for loss of biodegradable suspended solids. As a result of this relationship, the destruction of biodegradable suspended solids is often referred to as decay, and the first-order reaction rate coefficient is called a decay coefficient.

A number of variations of the aerobic stabilization processes are present, counting (i) mesophilic conventional, (ii) high-purity-oxygen, (iii) thermophilic and (iv) cryophilic aerobic stabilization. Mesophilic conventional aerobic stabilization is the most typically used aerobic stabilization process.

A general comparison of aerobic stabilization processes is provided in Table 2.4.

Table 2.4: Aerobic stabilization processes comparison

Process	Advantages	Disadvantages
Conventional	Proven process Simple operation High quality supernatant	Higher energy costs Long SRTs Poor dewaterability
Autothermal thermophilic	Low SRTs Smaller reactors Good dewaterability	Complex operation High energy costs Foaming
Aerobic-anoxic	pH control provided Less energy costs Higher quality supernatant	Longer SRTs Larger reactors Poor dewaterability

2.2.4.3 Conventional (mesophilic) aerobic stabilization

Conventional aerobic stabilization (CAS) is a relatively plain process. It consists of the addition of solids to an aerated vessel and their retention there for a period of time equal to the SRT. In the intermittent process, Figure 2.6a, solids are added and removed from the digester periodically, usually once per day. This process is used in conjunction with biological wastewater treatment systems in which solids wasted on a daily basis, usually over a relatively short time period. Digested solids are removed from the digester as necessary, depending on the downstream solids handling system. Solids may also be wasted from a biological wastewater treatment system on a more continuous basis, a practice often used in larger plants. Figure 2.6b illustrates an aerobic stabilization system that receives feed on a continuous basis. It looks like an activated sludge system, with feed solids displacing digesting solids to a gravity thickener. Supernatant overflows the thickener, while thickened solids are withdrawn from its bottom and returned to the digester. Solids which are thickened are also occasionally directed to solids handling, with the rate of thickened solids removal being tuned to maintain the wanted SRT.

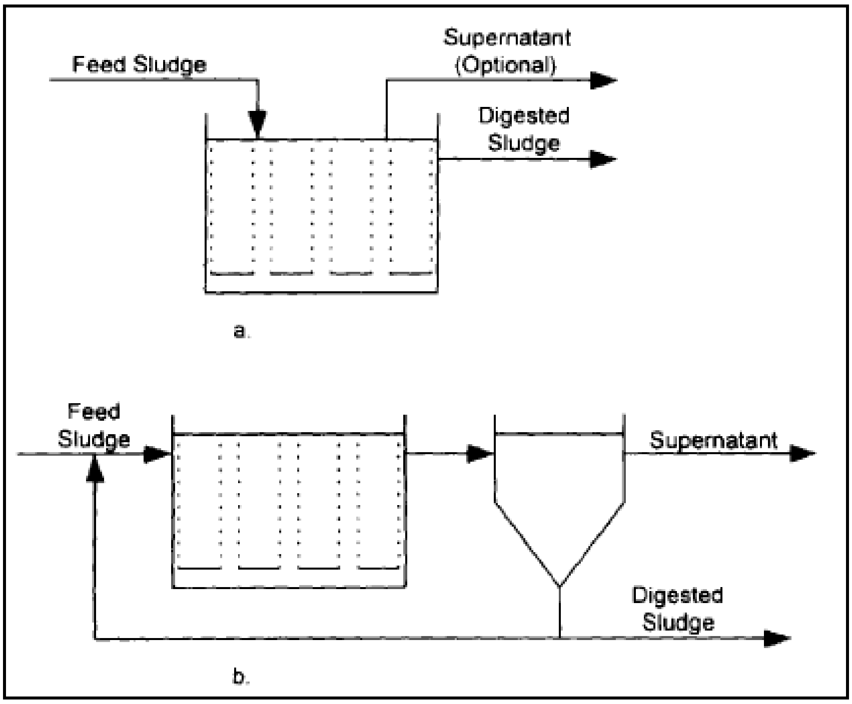

Figure 2.6: CAS: a. intermittent feed; b. continuous feed (with thickener)

Traditionally, conventional aerobic stabilization process was broadly used to stabilize waste solids from municipal and industrial WWTPs. Its advantages include simple design and operation, moderate costs. Its disadvantages include high energy costs, reduced biological energy during cold weather, alkalinity depletion, and poor pathogen reduction. If SRT is sufficiently maintained in one or more aerated tanks, much of the biodegradable organic matter added to the digester can be stabilized (WEF, 2008). However, because of the completely mixed nature of the reactor environment, some biodegradable organic matter remains unstabilized. Nitrification of released ammonia nitrogen results in consumption of alkalinity and low pH values, which inhibit stabilization. Because of these performance difficulties, relatively long SRT values were specified when solids disposal regulations were proposed and subsequently promulgated. These reasons caused a decline in the interest for conventional aerobic stabilization.

As Andreoli et al. (2007) explains, features to be taken into consideration for design of aerobic digesters are similar to those for activated sludge systems, such as:

- hydraulic detention time which, in this case, is equal to the solids retention time
- organic loading

- oxygen demand
- power requirements (supplying oxygen demand and maintaining sludge in suspension)
- temperature

The main design parameters for conventional aerobic sludge stabilization units are shown in Table 2.5.

Table 2.5: Design parameters for conventional aerobic sludge stabilization process

Parameters (Units)	Typical values
SRT (days @20^{o}C)	10-40
Volatile suspended solids loading (kg VSS/m^3·d)	1.6-4.8
Oxygen requirement (kg O_2/kg VSS reduced)	1.5-2.5
Mixing energy requirement	
Mechanical aerators (W/m^3)	20-40
Diffused aerators (L/m^3·min)	20-40
Dissolved oxygen (mg/L)	0.5-2
Volatile suspended solids reduction (%VSS)	35-50

Usually, an aerobic stabilization unit is operated through continuous feed of sludge with intermittent supernatant and digested sludge withdrawals. Supernatant is the clear liquid that forms above the settled solids in the digester. The digested solids are continuously aerated during filling and for the specified stabilization period after the tank is full. In some operations, the aeration system is shut down for 1 to 2 hours to allow the solids to settle and the supernatant to form (WEF, 2002). The supernatant is then decanted, allowing additional waste sludge to be added; thus, the solids concentration typically increases. The increase of solids concentration results from the decanting process. Throughout stabilization, decanting permits the solids to settle and the clear supernatant to be re-transferred to the treatment process.

2.2.4.4 Advanced aerobic stabilization processes

Advanced stabilization processes engage adaptation to the conventional stabilization design to attain complete stabilization, advance pathogen reduction and improve digester operation. Three types of advanced aerobic stabilization processes are explained as follows; high-purity-oxygen, autothermal thermophilic and cryophilic.

High-purity-oxygen aerobic stabilization:

High-purity oxygen is utilized in this aerobic stabilization process instead of air. Side stream flows and the resultant sludge are very similar to those obtained through conventional aerobic stabilization. Typical feed sludge concentrations may differ from 2 to 4%. High-purity-oxygen aerobic stabilization is mostly relevant in cold weather climates because of its relative insensitivity to changes in ambient air temperatures due to the increased rate of biological activity and the exothermal nature of the process.

High-purity-oxygen aerobic stabilization is practiced in either open or closed tanks. Because the stabilization process is exothermic in nature, the use of closed tanks will result in a higher operating temperature and a considerable increase in the rate of volatile suspended solids reduction. The high-purity-oxygen atmosphere in closed tanks is maintained above the liquid surface, and the oxygen is transferred to the sludge through mechanical aerators. In open tanks, the oxygen is introduced to the sludge by a special diffuser that produces minute oxygen bubbles. The bubbles dissolve before reaching the air–liquid interface. High operating costs are associated with the high-purity-oxygen aerobic stabilization process because of the oxygen generation requirement. Therefore, WEF (2008) indicates that high-purity-oxygen aerobic stabilization is commonly feasible only when used in combination with a high-purity-oxygen activated sludge process.

Autothermal thermophilic aerobic stabilization:

Autothermal thermophilic aerobic stabilization (ATAD) characterizes a difference from both conventional and high-purity-oxygen aerobic stabilization. In this process, the feed sludge is pre-thickened to provide a digester feed solids concentration greater than 4%. Dry solids (DS) content in the raw sludge as a rule lies in a favorable range between 5.0 % and 7.0 %. ATV-DVWK (2003) declares that a too extensive pre-thickening of the raw sludge from more than 8.0 to 8.5 % DS is not sensible as, due to the higher solid matter content, the viscosity of the sludge increases strongly. Oxygen transfer and mixing in the reactor are then weakened significantly.

The reactors are insulated to conserve the heat produced from the biological degradation of organic solids by thermophilic bacteria. Thermophilic operating temperatures in insulated reactors are in the range 45 to 70 °C, without external supplemental heat provided, other than the aeration and mixing devices located inside the vessels. Due to this event, the process is defined autothermal.

The major advantages of ATAD are as follows (WEF, 2008):

- decrease in retention times (smaller volume required to achieve a given suspended solids reduction) to approximately 5 to 6 days to achieve volatile solids reduction of 30 to 50%
- greater reduction of bacteria and viruses compared with mesophilic anaerobic stabilization

The major disadvantages of ATAD are as follows:

- poor dewatering characteristics of ATAD biosolids
- objectionable odors are formed
- lack of nitrification and/or denitrification
- high capital cost

Table 2.6 shows recommended design outlines for ATAD stabilization systems.

Table 2.6: Recommended design parameters for ATAD stabilization systems

Parameters (Units)	Typical Values
Number of reactors	2-3
SRTs (days)	6-8
Solids concentration (%DS)	4-6
Operating temperature (^{o}C)	40-55

<u>Cryophilic aerobic stabilization:</u>

The operation of aerobic digesters at low temperatures (less than 20 °C) is known as cryophilic aerobic stabilization. Although not widely used, research has been concentrating on optimizing the operation of these digesters. This research has suggested that the sludge age in the digester should be increased as the operating temperatures decrease, to maintain an acceptable level of suspended solids reduction.

2.2.4.5 Optimization of Aerobic Stabilization

Research was started in reaction to the new performance requirements for solids beneficial reuse, resulting in the identification of techniques that can improve process performance. According to Tchobanoglous et al. (2003) these techniques can be broadly grouped into the following three categories; (i) pre-thickening, which uses mechanical devices, such as gravity belt thickeners or gravity thickeners, to thicken before stabilization; (ii) staged operation, which uses either a tanks-in-series configuration or sequential batch reactor (SBR) operation to increase the plug-flow characteristic in the digester and reduce short-circuiting and (iii) aerobic–anoxic operation, which cycles the oxygen-transfer device on and off to allow denitrification to occur.

Pre-thickening:

The main advantages of this method include the following:

- increased SRT and volatile solids destruction: increasing feed sludge concentrations by thickening will result in longer SRTs with subsequent increased levels of volatile solids destruction.
- accelerated stabilization and pathogen destruction rate : Because the quantity of water that must be heated is reduced, the heat released as a result of the oxidation of the biodegradable organic matter can result in elevated digester temperatures and accelerate stabilization and pathogen destruction rates

Staged operation:

Conventional aerobic stabilization basins have been built as single basins, and, if multiple basins were designed, they were usually operated in parallel. Multiple tanks in series or in isolation operated in a batch operation have proven to improve both the pathogen destruction and standard oxygen uptake rate (SOUR). Probably the most practical alternative to a single-stage completely mixed reactor is staged operation, such as the use of two or more completely mixed digesters in series. The amount of processed sludge passing from inlet to outlet would be significantly decreased in comparison to single stage operation.

Aerobic–anoxic operation:

This technique enables operators to successfully nitrify/denitrify, control pH, recover lost alkalinity, and optimize aerobic stabilization, while saving energy. Because of the long SRTs required to accomplish solids stabilization, nitrifying bacteria typically grow in the digester even if they are not present in the feed solids. Furthermore, because of the relatively high feed solids concentrations typically used, the ammonia-N concentrations that develop are high, causing nitrification to deplete the alkalinity in the system, dropping the pH. An additional benefit is a small reduction in process energy requirements since some of the organic matter is oxidized by using nitrate- N generated through nitrification, rather than oxygen, as the electron acceptor.

The option in Figure 2.7a is a modification of intermittent conventional aerobic stabilization in which the oxygen transfer system is cycled on and off to create aerobic and anoxic periods during the digester operational cycle.

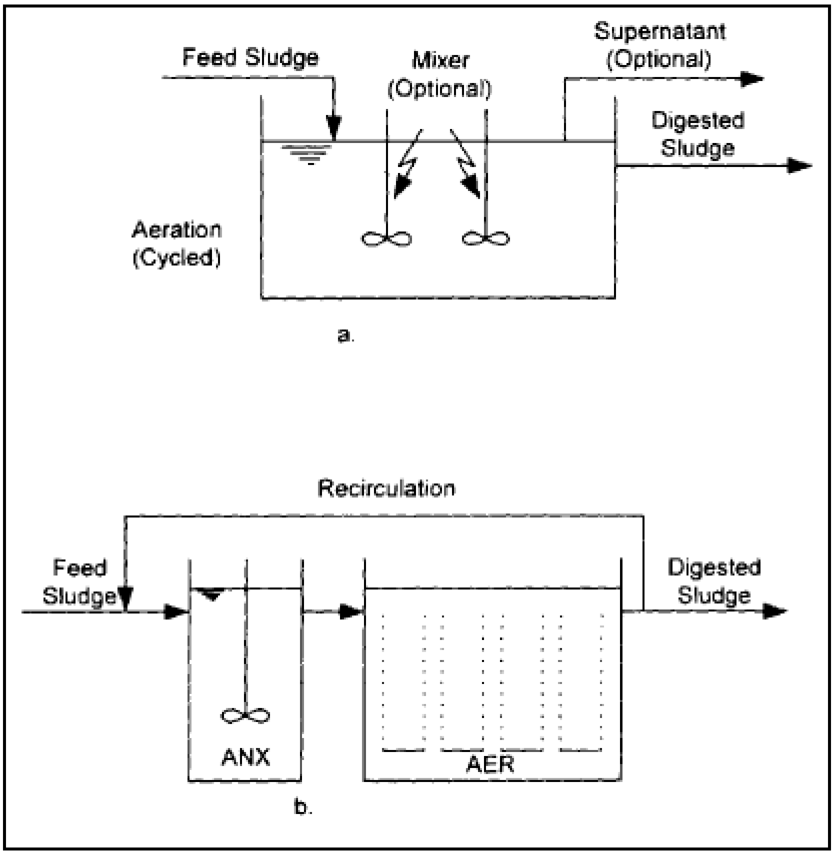

Figure 2.7: Aerobic-anoxic stabilization: a. intermittent feed; b. continuous feed

Other options involve the use of separate anoxic and aerobic zones, as shown in Figure 2.7b. SRTs and suspended solids concentrations in aerobic–anoxic systems are similar to those in conventional aerobic stabilization systems. Moreover, essential units and equipment for aerobic–anoxic systems are similar to those needed for conventional aerobic stabilization systems.

2.2.4.6 Aerobic stabilization units and equipment

Types of reactors:

Open or closed tanks can be used for aerobic stabilization. Open tanks are more common; however, in the last decade, more designers use covered and deeper tanks. Covers reduce freezing, heat loss, and surface evaporation. Covers combined with pre-thickening can increase the performance of conventional aerobic stabilization by increasing both the volatile solids reduction and pathogen destruction. In general, if the digester liquid temperature can be maintained at 20 °C all year, after thickening, the covers are not required (WEF, 2008). If it is likely to be that temperature is below that, it is feasible to consider covers.

Most aerobic stabilization units are built to tolerate very slight fluctuations in the first tank to take full advantage of oxygen transfer and mixing. Some aerobic digesters are designed with sloped floors so that digested sludge is drawn off the bottom others have a constant weir overflow design. Aerobic digesters are constructed of reinforced concrete and steel. In cold climates, steel tanks that are above ground should be insulated. In cases where the steel and concrete tanks are underground, they are rather well insulated by the soil.

Piping requirements:

Minimal piping requirements should incorporate provisions for feeding sludge; decanting supernatant, where applicable; withdrawing digested sludge; and supplying air for aeration. Piping planning for sludge lines flushing with plant effluent should also be presented.

Pumps:

A number of different types of pumps have been used to transfer sludge to aerobic stabilization units. Both positive displacement pumps and centrifugal pumps have been used successfully for this purpose. Airlift pumps and non-clog pumps draw off the thickened, digested sludge for transferring between basins, dewatering, or disposal.

Aeration equipment:

Either air or pure-oxygen transfer equipment, such as conventional mechanical aerators, coarse-bubble diffusers, tine-bubble diffusers, or jet aerators, supply the air (oxygen) needs for aerobic stabilization. The best device not only should be capable of developing the required oxygenation and mixing, but should also provide flexibility. As indicated in WEF (2002), air requirements typically range from 0.5 to 0.6 $L/m^3 \cdot s$ for the treatment of secondary biological sludges, and from 0.75 to 1.1 $L/m^3 \cdot s$ for the treatment of primary sludges. Required power density for aeration and thorough mixing is 50 W/m^3 (ATV-DVWK, 2003).

Diffused aeration equipment:

In aerobic digesters, fine-bubble ceramic diffusers should not be equipment of choice because they are especially susceptible to clogging. Typically, floor-covering, submerged-header air diffusers are found near the bottom of the digester, toward one side, to induce a spiral or cross-roll mixing pattern. The most widely used air diffusers are the small- and large-bubble types. Submerged header air diffused systems: tend to add heat to the digester and are not greatly affected by foaming conditions, they also may require the entire assembly to be removed for cleaning if it becomes clogged or plugged during the anoxic (optional) operation.

Mechanical aerators:

Mechanical surface aerators, in either free-floating or fixed installations, are efficient in oxygen transfer. Characteristically, mechanical surface aerators supply oxygen efficiently to aerobic digesters, if the desired solids concentration in the basin is less than 2.5% solids. They have minimal maintenance requirements and are greatly affected by foaming conditions. In addition, these types of aerators are greatly affected during cold weather by ice buildup.

Submerged mechanical aerators:

Submerged mechanical aerators include a rotating submerged impeller mounted on a drive shaft extending vertically into the aeration basin. Compressed air is supplied beneath the impeller, where it is sheared into bubbles and pumped into the basin. Generally, submerged mechanical aerators are unaffected by foaming or icing conditions.

Blowers:

For aerobic stabilization, centrifugal blowers and rotary positive displacement air blowers are proper. As a minimum, for a two-stage digester system, three blowers are suggested.

Specific mixing and aerating equipment:

Various aeration systems have been used in ATAD systems, including floor-mounted jet aspirator (Siemens Water, 2009) or jet aeration, side-mounted aspirating aeration (Fuchs, 2009), top-mounted aspirator aeration (MGD Process, 2009) and pump and venturi system. With all air aspirating systems, the equipment provides both mixing and oxygen transfer.

Control equipment:

Aerobic stabilization systems generally include automatic pH control instruments. The typical automatic pH control system consists of a pH electrode placed within the digester that measures the pH and provides a signal to chemical feed pumps if the desired pH range is not being achieved. The pH control systems can also be used to control the blowers to provide a controlled airflow to the basins, which will provide the operator with the capabilities to optimize the process and operate in a simultaneous nitrification and denitrification mode. In order to provide a aerobic-anoxic operation blowers can be controlled to function in a on-off fashion.

2.2.4.7 Process performance

Performance of an aerobic stabilization system is calculated by its efficiency while digesting and altering waste sludge to a proper product for later processing or disposal.

WEF (2008) applies the following parameters in order to assess the performance of aerobic stabilization systems:

1. Standard oxygen uptake rate (SOUR)
2. Pathogen reduction
3. Volatile solids reduction
4. Solids retention time x temperature (days·°C)
5. Nitrogen removal in biosolids

6. Sludge dewaterability
7. Supernatant quality

Standard oxygen uptake rate:

Oxygen consumption rate by the microorganisms is linked to the rate of biological oxidation. The SOUR of 1.5 mg oxygen/g total solids·h at 20 °C was selected by United States Environmental Protection Agency (U.S. EPA) to indicate that an aerobically stabilized sludge has been adequately reduced in vector attraction.

To conclude the level of biological activity and the resulting solids destruction taking place in the digester, oxygen uptake rate can be used. The SOUR is becoming a more common testing procedure for most operators instead of using the traditional volatile solids reduction. An oxygen uptake rate for a well-digested sludge from the aerobic digestion process ranges from 0.1 to 1.0 mg oxygen/g total solids·h well below the required 1.5 mg oxygen/g·h by U.S. EPA standards (WEF, 2008).

Pathogen reduction:

Throughout aerobic stabilization, the degree of pathogen reduction is comparable to that achieved by biological reduction in that it increase as the temperature and SRT increase. Reductions of one order of magnitude are achieved at temperatures and SRT values of 35°C and 15 days, or 25 °C and 30 days (WEF, 2002). Pathogen reduction is similar to solids reduction in that little pathogen reduction can be expected at temperatures less than 10 °C, while significant reduction may be achieved at temperatures higher than 20 °C. Even though it is acceptable by U.S. EPA standards to operate at 15 °C, for economic reasons and performance reliability, the author recommends designing and operating the plant at a minimum of 20 °C. In addition, Turovskiy (2001) suggests that aerobic stabilization process with a SRT of 40 days and a temperature of 20 °C leads to relatively safe levels of coliforms and pathogenic viruses.

Volatile solids reduction:

Aerobic stabilization causes the destruction of VSS. According to Tchobanoglous et al., volatile solids reductions ranging from 35 to 50% are achievable by aerobic stabilization (2003). The destruction of biodegradable suspended solids can be distinguished as a first-order reaction and it is considerably affected by temperature.

Solids retention time x temperature:

Solids retention time (SRT) is the total mass of biological sludge in the reactor, divided by the mass of solids that are removed from the process on a daily average. In the past, SRTs of 10 to 20 days were the norm for the design of aerobic digestion systems. Typically, increased SRT results in an increase in the degree of volatile solids reduction. With respect to temperature, degradable sludge and the effect it can have on volatile solids reduction, the SRT x temperature product (days·°C) curve can be used to design digester systems. The original U.S. EPA SRT x temperature curve, developed in the late 1970s was updated by incorporating data from extensive pilot studies conducted over three years with data from three full-scale installations results show a process design based on 600 days °C is likely to provide VSS reductions over 40%. Figure 2.8 adapted from Tchobanoglous et al. (2003) presents VSS reductions interrelated with temperature and SRT.

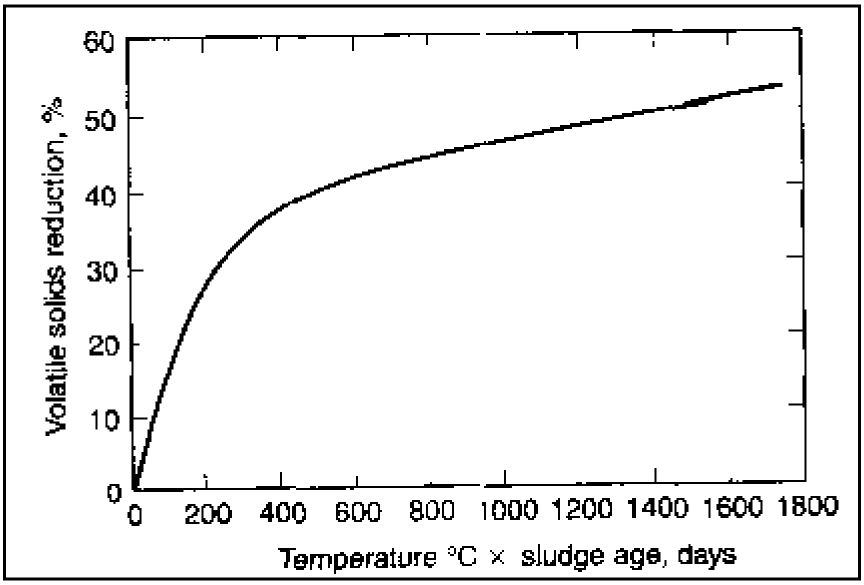

Figure 2.8: VSS reduction in aerobic stabilization relation to temperature and SRT

As Grady et al. (1999) demonstrates, at longer SRTs, debris accounts for major part of the remaining solids, suggesting that little additional solids destruction will occur, even if the SRT is extended greatly (Figure 2.9). This characteristic should be kept in mind, when selecting the SRT for an aerobic digester. A point may quickly be reached at which further increases in SRT will have minimal effect, making expenditures for additional tank volume questionable. That point will depend on the nature of the influent solids, their biodegradability, and the temperature of the system.

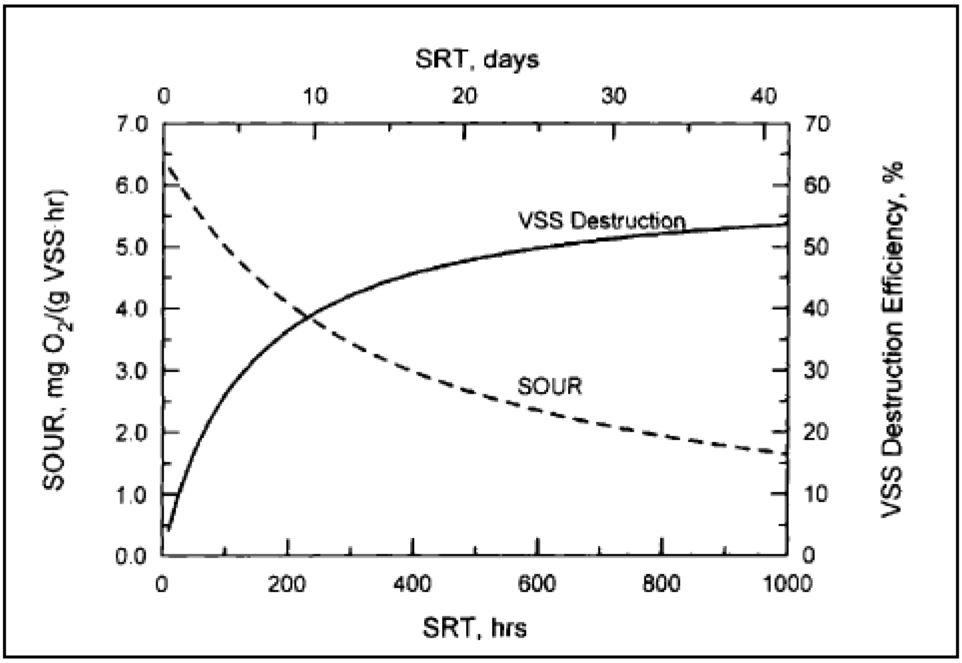

Figure 2.9: Effect of SRT on the VSS destruction and SOUR

Nitrogen removal in biosolids:

Operated in the aerobic–anoxic mode, aerobic stabilization process offers full nitrification and denitrification and results in a total nitrogen reduction. The annual design loading rates for land application of biosolids is typically limited by the nitrogen loading rate. Because nitrification is inhibited in the ATAD process, the most ideal process to meet these requirements is the conventional process operated in the aerobic– anoxic mode.

Sludge dewaterability:

Dewaterability of the aerobically stabilized sludges are typically poorer than those of anaerobically stabilized sludges. In general, it has been observed that sludge type has the greatest effect on the quantity of chemicals required for chemical conditioning. Factors affecting the selection of the type and dosage of conditioning agents are the properties of solids and type of mixing and dewatering devices to be used. Significant solids characteristics include source, solids concentration, age, pH, and alkalinity.

Sludges those are difficult to dewater and require larger doses of chemicals generally do not yield cake as dry as other sludges and have a poorer quality of filtrate or centrate a number of plants have shown improvement in their sludge characteristics when changes were made from traditional conventional aerobic stabilization to aerobic–anoxic operation (WEF, 2008).

Supernatant quality:

The supernatant or filtrate from aerobic stabilization compared to anaerobic stabilization, should be low in soluble biochemical oxygen demand (BOD), total suspended solids (TSS), total kjeldahl nitrogen (TKN) and total phosphorus (TP), for both batch and continuous-flow operations. Table 2.7, adapted from WEF (2008), lists characteristics of acceptable supernatant values from aerobic stabilization processes. To improve these parameters, it is necessary to operate in aerobic–anoxic operation. Controlling the availability of necessary quantities of carbon source required denitrification to allow for full nitrification and denitrification will enhance supernatant quality. Preserving a neutral pH of 7.0 will furthermore improve nitrification and denitrification.

Table 2.7: Acceptable characteristics of aerobic stabilization supernatant

Parameters (Units)	Acceptable range	Typical Values
pH	5.9-7.7	7.0
BOD_5 (mg/L)	10-1700	500
Soluble BOD_5 (mg/L)	5-170	50
TSS (mg/L)	50-2000	1000
TKN (mg/L)	10-400	170
TP (mg/L)	20-240	100

2.2.4.8 Process control

The important factors in controlling the operations of aerobic digestion are similar to those for other aerobic biological processes. The primary process indicators for monitoring aerobic digesters on a daily basis are temperature, pH, dissolved oxygen, odor, and settling characteristics, if applicable. Ammonia, nitrate, nitrite, phosphorus, alkalinity, SRT, and SOUR are secondary indicators that are useful in monitoring long-term performance and for troubleshooting problems associated with the primary indicators. Monitoring helps control process performance and serves as a basis for future improvements.

Table 2.8 provides a list of both the primary and secondary monitoring parameter indicators. Analysis frequency should be increased during startup and during those times when large changes are made to operating conditions, such as sludge flowrate, sludge source, change in polymer, large increase or decrease in solids concentration of feed, or large increase or decrease in temperature of feed.

Table 2.8: Recommended values for primary and secondary parameters

Parameters (Units)	Frequency	Typical Values
Temperature (^oC)	Daily	20
pH	Daily	7.0
Dissolved oxygen (mg/L)	Daily	1.0
Alkalinity (mg/L)	Weekly	>500
Ammonia-nitrogen (mg/L)	Weekly	<20
Nitrate (mg/L)	Weekly	<20
Nitrite (mg/L)	As required	<10
Phosphorus (mg/L)	As required	<5
SOUR (mg oxygen/g total solids·h)	As required	<1.5

Most important operational parameters, temperature, pH and dissolved oxygen are discussed under following topics.

Temperature:

The operating temperature of an aerobic stabilization system significantly affects process performance. High temperature allows higher rates of microbial metabolic activity, leading to a shorter retention time required to achieve a certain level of solids destruction and a good degree of inactivation of pathogenic organisms (Bernard and Gray, 2000). The liquid temperature in an aerobic digester significantly affects the rate of volatile solids reduction that increases as temperature increases. As with all biological processes, the higher the temperature, the greater the efficiency is. At temperatures lower than 10 °C the process is less effective (WEF, 2002). In most aerobic digesters temperature is a function of ambient weather conditions and is not controlled. In considering the temperature effects, heat losses should be minimized by using concrete instead of steel tanks, placing tanks below grade or providing insulation for above-grade tanks and using subsurface instead of surface aeration.

pH:

As with other biological systems, the aerobic digestion process performs better at either a neutral or slightly higher pH. The results suggest that either pH adjustment or increased alkalinity will improve performance and dewaterability.

Two products of aerobic digestion that tend to lower the digester pH are carbon dioxide and hydrogen ions. A pH drop can occur when ammonia is oxidized to nitrate if the alkalinity of the wastewater is insufficient to buffer the solution. In situations where the buffering capacity of the sludge is insufficient, it may be necessary to chemically adjust the pH.

Dissolved oxygen:

Also another critical parameter in the aerobic digestion process is dissolved oxygen (DO). Maintaining adequate oxygen concentrations allows the biological process to take place and prevents objectionable odors. As WEF (2002) puts out, in aerobic stabilization units, DO concentrations typically range from 0.5 to 2.0 mg/L. Inadequate DO levels result in incomplete digestion and, more importantly, odor problems.

2.2.4.9 Operational monitoring, data collection and laboratory control

For the most part, aerobic digestion is a self-regulating process, unless the process is overloaded or the equipment is inoperative. Routine operational surveillance includes analytical testing and periodic checks of electrical and mechanical equipment, such as seals, bearings, timers, and relays. From an operator's point-of-view, there are two interrelated types of issues that typically could require troubleshooting; (i) equipment and (ii) process.

Consistent data collection and process control through laboratory analysis are essential in the efficient operation of the treatment system. According to WEF (2008), analysis for total solids, volatile solids, dissolved oxygen; ammonium, nitrate, phosphorus, pH, temperature, flowrate, airflow rates, solids concentration, fecal coliforms, SOUR, and alkalinity of the raw and digested sludges provide the minimum surveillance for operating the aerobic stabilization unit.

2.3 Post-Stabilization Disposal Alternatives

While the diversity of unit processes for sludge treatment has increased dramatically there are still only three basic ultimate disposal routes for processed sludge; (i) landfill, (ii) land application and (iii) incineration (Spinosa and Vesilind, 2001). None of these end-uses are fundamentally either good or bad; each one is simply more or less appropriate for a given situation. Each utilization or disposal route has specific inputs, outputs and impacts. In this study only landfill and land application are considered since these disposal methods do require sludge stabilization. On the other hand, sludge stabilization is not a prerequisite for incineration and in fact prior to incineration sludge stabilization should be avoided because it limits incineration efficiency due to removal of organics from the sludge.

2.3.1 Landfill

Landfilling is a convenient solution where enough space is available locally at reasonable fees. It is applied, especially when reuse is not of primary importance, being possibly limited only to biogas recovery. There are two possibilities for landfilling sludge: (i) mono-deposits, where the landfill is only used for sludge and (ii) mixed-deposits, when the landfill is used for municipal wastes as well (Spinosa and Vesilind, 2001). Mixed-deposits are much more common as there is no specific technical constraint in the landfill design and operation for the disposal of sludge.

Well-dewatered sludges are suitable for landfill in order to avoid poor compacting and low consistency at landfill sites. In addition, good level of biological stability is also necessary to prevent possible emissions of bad odors and overload in leachate treatment system. Possible inputs and outputs of a landfill site are shown in Figure 2.10 adapted from EC (2001).

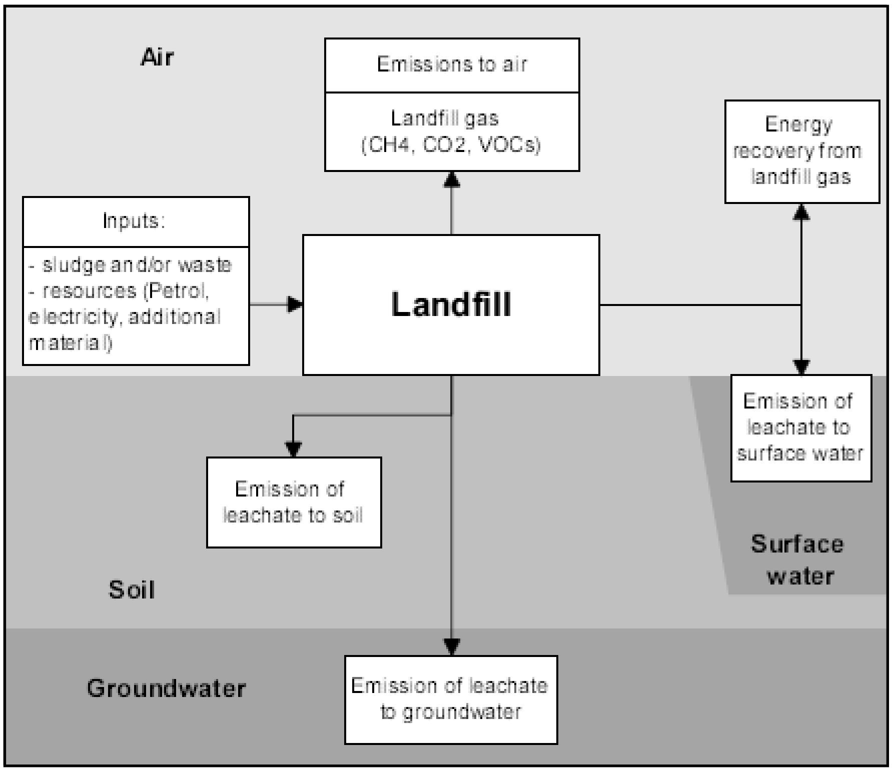

Figure 2.10: Inputs and outputs of landfill operations

So far, landfilling has been a major route for sludge disposal. However, according to EC (2001) it should be a limited method in the future, because of the European legislation on the landfilling of waste, which limits biodegradable waste going to landfills. One good reason to regard landfilling as a non-sustainable solution for the disposal of organic waste such as sludge is the fact that the leachate from landfill sites has to be treated for many years, even after the site has been closed and reclaimed (Nowak, 2006). Furthermore, with sludge away from landfill sites, available capacity can be used for wastes which treatment or reuse is not possible and for longer periods.

2.3.2 Land application

Land application also known as land spreading or agricultural use is a beneficial use of municipal biosolids and in some cases blended with additional organic waste. Sludge can be reused as an organic soil, nutrient rich source such as a fertilizer or soil amender. Several advantages include recycling of nutrients and organic matter, which positively affect soil structure. Direct application may be variable over time, depending on; crop type and weather conditions. If sludge production is continuous, composting is often a valid alternative which produces a safe and hygienic product that can easily stored, transported and land applied.

According to Spinosa and Vesilind (2001), land application may not be a viable option due to:

- lack of land availability (especially land within economical transportation distance)
- inability to meet heavy metals criteria
- traffic density arising from its transportation

If in some cases volume reduction becomes an important precondition than sludge drying may be a viable treatment method prior to land application. Possible inputs and outputs of land application are shown in Figure 2.11 adapted from EC (2001).

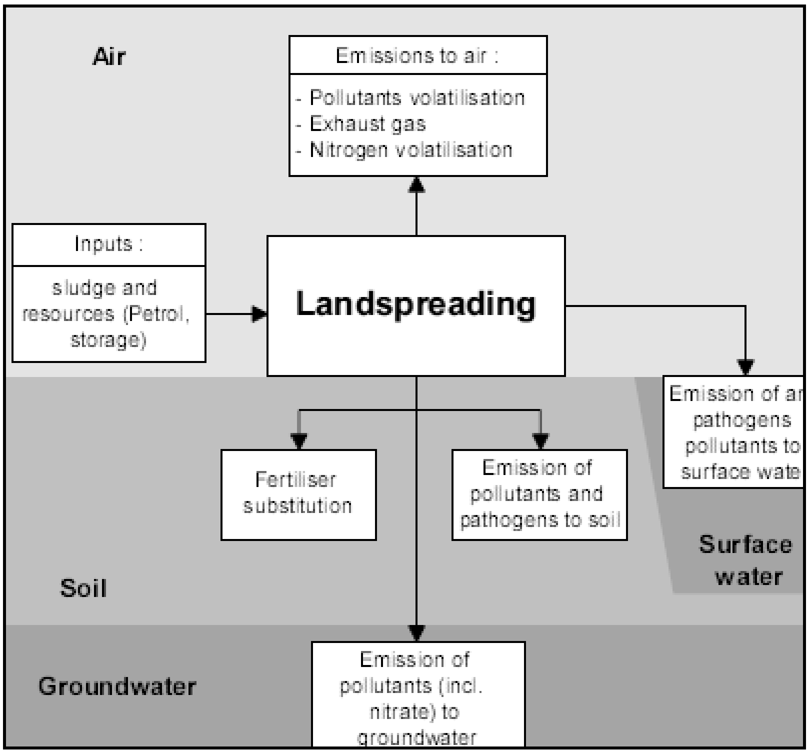

Figure 2.11: Inputs and outputs of land application operations

Particularly for small and medium wastewater treatment plants, which are close to farming lands and serve non-industrialized areas, land application is likely to remain as a major sludge disposal option.

3. BREWING INDUSTRY ENVIRONMENTAL IMPACT

3.1 Brewing Processes

The raw supplies for beer commonly consist of barley malt, adjuncts, hops, water and yeast. Production methods will vary from brewery to brewery as well as according to beer types, brewery equipment and local legislation. The main processes however are the same; (i) wort production, (ii) fermentation/filtration and (iii) packaging.

Wort production:

The Brewers of Europe (2002) defines wort production process as follows; malt is delivered to the brewery, weighed, conveyed, cleaned, stored and made available for wort production. After milling of the malt and preliminary treatment of the adjuncts to facilitate the extraction, the malt and adjuncts are mixed with brewing water to form a mash. Adjuncts are a supplementary carbohydrate supply added either to the mash kettle as starch (maize grits or rice) or alternatively to the wort kettle as sucrose or glucose / maltose syrup. The mash is heated following a pre-set time-temperature programme, in order to convert and dissolve substances from the malt and the adjuncts in the brewing water.

Extraction is accomplished through a combination of simple dissolution and the influence of the natural enzymes formed during the malting. The substances dissolved in the water are collectively called the extract. The solution of extract and water is called the wort. When the mashing is completed, the insoluble solids, called the brewers grains, are separated from the wort by straining.

The wort is boiled with hops and hop extracts releasing bitter substances and oils, which are dissolved in the wort. During boiling a precipitate consisting mainly of proteins is obtained (trub) and the bitter substances are isomerised which increases their solubility. After separation of the trub, the finished wort is cooled to approx. 8-20°C depending on the yeast strain in question and the fermentation process chosen. The cooled wort is after transferred to the fermentation area.

Figure 3.1 shows the most important functions of the wort production.

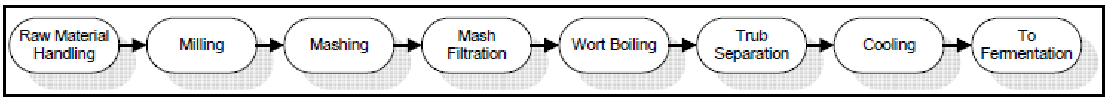

Figure 3.1: Wort production, adapted from The Brewers of Europe (2002).

Fermentation/filtration:

The cold wort is aerated and pitched, i. e. yeast is added. Oxygen (air) is necessary to support development of the yeast to a state and amount capable of fermenting wort efficiently. Fermentation is an anaerobic process; the yeast metabolizes the fermentable carbohydrates in the wort forming alcohol and carbon dioxide. A large number of different compounds, such as higher alcohols, esters, aldehydes, etc., influencing the aroma and taste of the beer, are also produced (The Brewers of Europe, 2002).

When the so-called main fermentation is completed and the yeast has been harvested, the green beer matures at lower temperatures. At this stage, the yeast decomposes certain undesirable constituents of the green beer, the beer is enriched with carbon dioxide, the residual extract is fermented and yeast and other precipitates settle.

However, the fine clarity expected by the consumer from most beer types is still missing. This is achieved by filtering the beer. Kieselguhr is used as filtration aid in most cases. During filtering, yeast cells still contained in the beer and other substances causing turbidity and any bacteria that might cause the beer to spoil, are removed. The filtered beer is pumped to the so-called bright beer tanks.

Figure 3.2 shows the most important functions of fermentation/filtration.

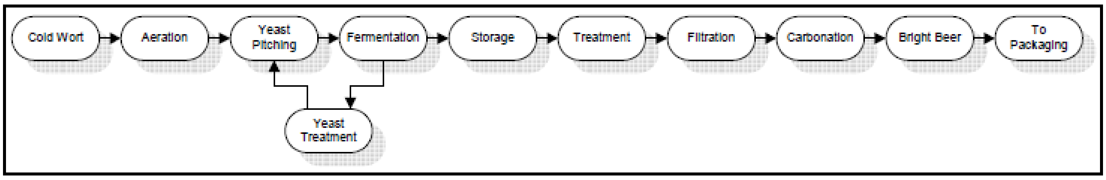

Figure 3.2: Fermentation/filtration, adapted from The Brewers of Europe (2002).

Packaging:

From the bright beer tanks, the beer is pumped to the packaging area where it is bottled, canned or kegged. During this final operation, it is important that the beer is prevented from getting into contact with oxygen and no carbon dioxide is lost as the beer was previously carbonated to specifications (The Brewers of Europe, 2002).

Packaging lines may be equipped quite differently, not only with respect to packaging material but also with respect to the level of automation and inspection.

Returnable bottles require thorough cleaning. The bottle washer consumes large quantities of energy, water and caustic. Furthermore, substantial quantities of wastewater are discharged. The use of non-returnable packaging material reduces the consumption of energy, water and caustic, therefore reducing wastewater generation.

In packaging lines using non-returnable bottles and cans, the bottles/cans are only flushed with water before filling. Alternatively, compressed air is used to blow out any dust particles. If kegs are used, they are cleaned and sterilized with steam before filling (The Brewers of Europe, 2002).

Figure 3.3 shows the most important functions of the packaging lines for returnable/non-returnable bottles, cans and kegs.

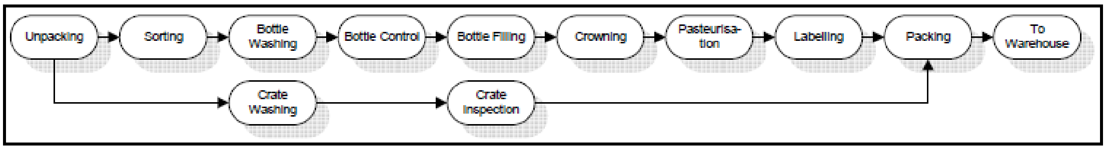

Figure 3.3: Packaging, adapted from The Brewers of Europe (2002).

3.2 Waste Profile

The major public concern of breweries has occasionally been about wastewater. Locally, the odor and the noise from the operation may cause public concern. Typical materials balance for a brewery is presented in Figure 3.4.

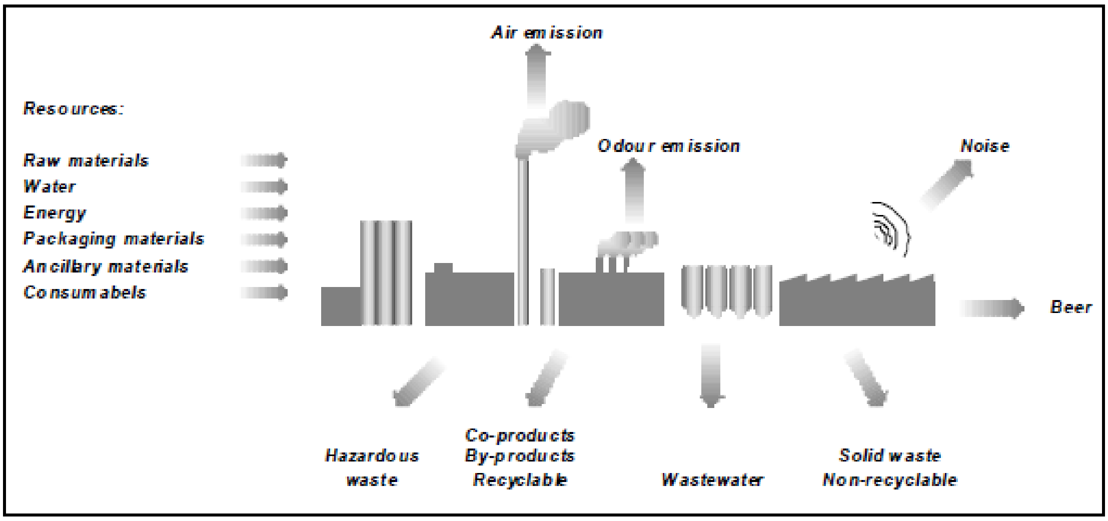

Figure 3.4: Environmental impact from a brewery.

In order to provide a more focused perspective brewing industry's waste profile is explained under three main categories; (i) water consumption, (ii) wastewater and (iii) solid waste (including co-, by-products and hazardous waste). Subject of wastewater is broadly discussed in the following topic.

Water consumption:

Water may be supplied to the brewery from sources of ground water, surface water or treated drinking water. Water will leave the brewery as beer, as a part of by-products (brewers grains and excess yeast), wastewater or as steam.

Water consumption for modern breweries generally ranges from 4 to 10 hl/hl of beer produced (EC, 2006). The water consumption figure varies depending on the type of beer, the number of beer brands, the size of brews, the existence of a bottle washer, how the beer is packaged and pasteurized, the age of the installation, the system used for cleaning and the type of equipment used.

As indicated by EC (2006), some examples of possible water saving measures are identified below:

- Closed-circuit water recycling
- Optimization of CIP (cleaning-in-place)
- Re-use of wash-water
- Spray/jet upgrades
- Automatic shut-off

Solid waste:

Solid materials enter the brewery in the form of raw and ancillary materials. The solid material leaves the brewery as co-, by-products (brewer's grains, surplus yeast and spent kieselguhr), packaging material, solid waste and hazardous waste. In general, a very small amount of hazardous waste is produced, such as spent laboratory chemicals and batteries.

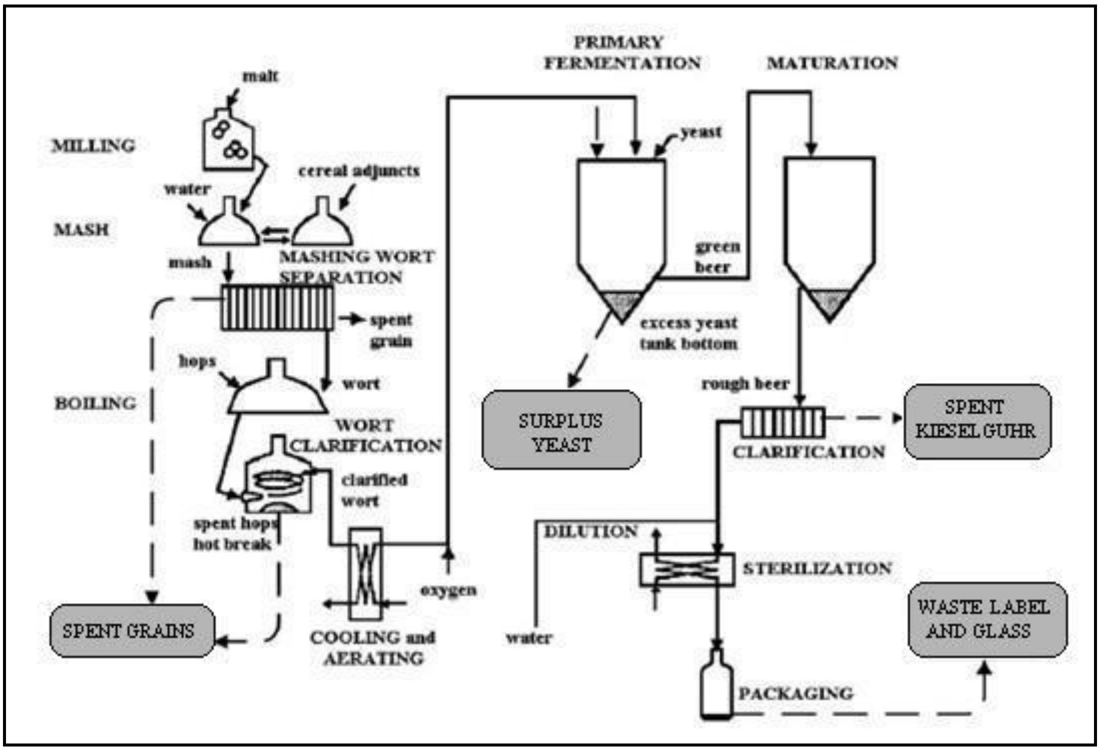

Figure 3.5: Brewing process and solid waste, adapted from Fillaudeau et al. (2005).

The amount of surplus yeast slurry is 2-4 kg (10-15% dry matter content) per hl beer produced (The Brewers of Europe, 2002). This surplus yeast may contain as much as 1.5–2.5% of the total beer production and it is usually worthwhile to recover (via vacuum filter, membrane filter press, plate press etc.) at least a portion of this beer. According to The Brewers of Europe (2002), the yeast suspension has a very high COD value (200,000 mg/L) therefore; disposal of surplus yeast into the WWTP should be avoided. Spent kieselguhr is wasted 90-160 g/hl beer produced with an average COD value of 80,000 mg/L.

The co-, by-products are in general useful, and many different applications have been reported (EC, 2006):

- malt dust as animal fodder, mixing into brewer's grains, utilization in the production
- brewer's grains as animal fodder, including trub from the whirlpool
- surplus yeast as animal fodder, yeast pills, cosmetics, pharmaceutical industry, spreads
- spent kieselguhr from the beer filtration can be used in the cement industry
- broken glass from the packaging lines can be reused for glass manufacturing
- label pulp from the washing of returnable bottles can be reused in paper manufacturing
- cardboard and paper from the supply of ancillary materials can be reused by paper factories pending upon the pulp quality

3.3 Wastewater and Sludge Characteristics

The wastewater discharge will be equal to the water supply subtracted the produced beer, evaporated water in brewery and utility plants and the water present in the by-products and solid waste. It is reported by The Brewers of Europe that in modern breweries 3–9 hl of wastewater is generated per hl of beer (2002).

Organic material mainly enters the brewery in the form of raw materials such as malt and adjuncts. Organic materials will mainly leave the brewery as beer, by-products and wastewater. In order to reduce the organic content of the wastewater focus must be put on the loss of beer and on collection/disposal of co-, by-products. The wastewater is very variable and the pollution load of the different steps do not follow the volumes throughput, e.g. bottle cleaning produces a high amount of waste water but with only a low organic load, while waste water from fermentation and filtering account for only about 3% of the total waste water volume but 97% of the COD load (EC, 2006).

The potential largest COD discharging processes are:

- brewer's grains
- surplus yeast
- trub

- weak wort discharge.
- emptying of and rinsing water from kettles.
- emptying of process tanks.
- pre- and after-runs from kieselguhr filtration and filling
- rejected beer in the packaging area
- breakage of bottles in the packaging area.
- ancillary materials used in packaging area e.g. adjective for bottle washer, conveyor lubrication and label glue.

Bio-essays such as, activated sludge oxygen consumption inhibition test, usually show that the respiration is increased compared to that of ordinary municipal wastewater (EC, 2006). Also low COD/BOD_5 ratios indicate that brewery wastewater is highly biodegradable.

As indicated by EC (2006), suspended solids in the wastewater originate from the discharge of byproducts, kieselguhr and possible label pulp from the bottle washer.

Total nitrogen (TN) in the wastewater originates from discharge of yeast and cleaning agents e.g. nitric acid that can be a part of the detergents used for tank cleaning. In connection with the maintenance of the cooling plant ammonia (NH_3) discharge may occur.

Phosphorus in the wastewater originates mainly from the detergents used for tank cleaning.

The usage of acids and caustic for the cleaning of process equipment and returnable bottles results in large variation of the pH in the wastewater.

Heavy metals are normally present in very low concentrations. Wear of the machines, especially conveyors in packaging lines, may be sources of nickel and chromium.

Adapted from EC (2006), Table 3.1 shows the characteristics of untreated wastewater from breweries. In terms of pollution load, Table 3.2 presents the ranges valid for modern breweries.

Table 3.1: Untreated wastewater characteristics for breweries

Parameter (Unit)	Range
BOD_5 (mg/L)	1000-1500
COD (mg/L)	1800-3000
SS (mg/L)	10-60
TN (mg/L)	30-100
TP (mg/L)	30-100
pH	3-13

Table 3.2: Wastewater pollution loads for breweries

Parameter	Unit	Range
COD	kg/hl beer	0.8-2.5
COD/BOD_5	-	1.5-1.7
SS	kg/hl beer	0.2-0.4

As EC (2006) reports, typical sludge generation will be in the order of 0.45-0.55 kg SS/kg BOD removed. The excess sludge can be a significant part of the breweries' solid waste disposal operations and costs. This is especially true for aerobic treatment systems where large quantities of sludge are generated.

3.4 Brewery Wastewater Treatment Plant for Case Study

For case study, a full-scale brewery wastewater treatment plant was used. Samples were taken from this plant and in addition, reactors setup in laboratory was based on operation parameters also acquired from the same plant.

The brewery wastewater treatment plant includes physical units for primary treatment, secondary treatment is composed of anaerobic and aerobic units and sludge treatment involves two steps, thickening and dewatering. Flowchart diagram of the wastewater treatment plant is shown in Figure 3.6.

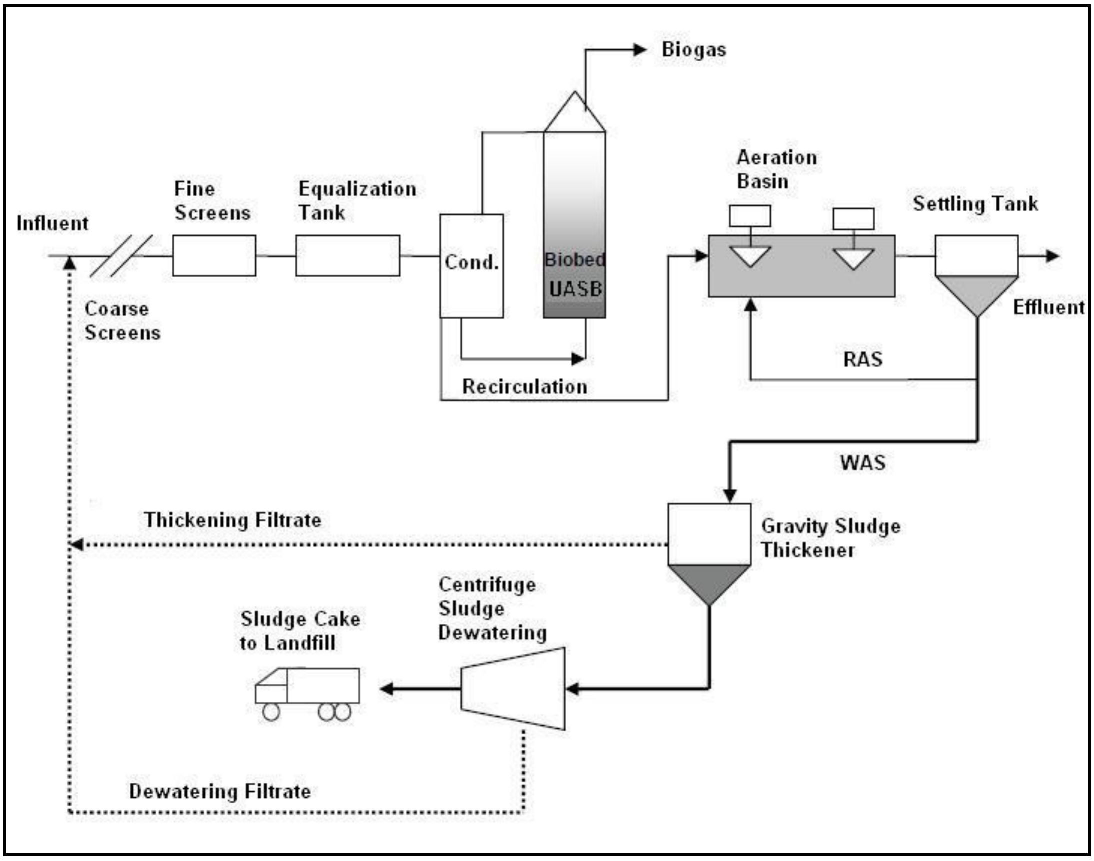

Figure 3.6: Brewery wastewater treatment plant flowchart diagram

The brewery wastewater treatment plant operates on a daily average flowrate of 1300 m^3/day and includes following biological treatment units and capacities:

- UASB Reactor (585 m^3) + Conditioning Tank (150 m^3)
- Aeration Basin (2500 m^3) + Settling Tank (Ø23, 4.70 m side water depth)

As well as following sludge treatment units and capacities:

- Gravity Thickener (125 m^3)
- Centrifuge Decanter (10 m^3/h)

All related analysis results (COD and SS) were obtained from plant’s operating staff, overall range of values (July, 2009) are presented in Table 3.3.

Table 3.3: Wastewater COD and SS range values acquired from the plant

Parameter	Unit	Range
Equalization effluent COD	mg/L	3500-4200
UASB effluent COD	mg/L	850-1000
Final effluent COD	mg/L	50-70
Equalization effluent SS	mg/L	600-900
UASB effluent SS	mg/L	500-750
Final effluent SS	mg/L	25-40

When compared to typical literature values, COD and SS values given above seem to be on higher levels. Main reason for increased SS and COD concentrations is that in this plant spent yeast is also discharged to wastewater treatment plant. As presented in Table 3.4, a previous study (Personal communications, 2009) on a similar brewery indicates that influent wastewater characterization in case of yeast discharge is considerably different from the case without yeast discharge.

Table 3.4: Influent wastewater characterizations with and without yeast discharge

Parameter	Unit	With yeast	Without yeast
SS	mg/L	508	235
VSS	mg/L	165	125
TCOD	mg/L	4425	1565
SCOD	mg/L	3195	1145

Furthermore, all related operating parameters for activated sludge system in the plant were also obtained from plant's operating staff; typical values are presented in Table 3.5.

Table 3.5: Operational parameters typical values

Parameter	Unit	Typical
Flowrate	m^3/day	1300
MLSS	mg/L	3500
HRT	hours	46
SRT	days	10
SVI	ml/g	120
Sludge cake amount (dry weight-disposed)	tones/day	1.5
Sludge cake dry matter ratio	%DS	22

ATV-DVWK (2000) suggests SRT values 20 days or higher for sludge stabilization within aeration basin. As can be seen, due to insufficient SRT values, sludge stabilization within the aeration basin is not possible for the plant; therefore, a separate stabilization unit is required.

4. MATERIAL AND METHOD

In material and method section, details about sampling, reactors setup, aerobic stabilization analysis as well as sludge and wastewater parameters analysis methods and related material/equipment were presented.

4.1 Sampling

Wastewater samples were taken from equalization tank effluent in order to represent raw wastewater which is only treated by physical units and is to be treated by biological processes. Activated sludge samples were taken from aeration basin, representing mixed liquor suspended solids (MLSS).

4.2 Reactors Setup and Acclimation Period

In order to reflect four different influent COD concentrations, four cylinder reactors (reactor-1, -2, -3 and -4) were set up, each one was operated with a volume of 4 liters during acclimation period. Reactor-1 indicates the reactor with an influent TCOD value of 1000 mg/L, in a similar fashion Reactor-2, -3 and -4 indicate TCOD values of 2000, 3000 and 4000 mg/L respectively (Figure 4.1).

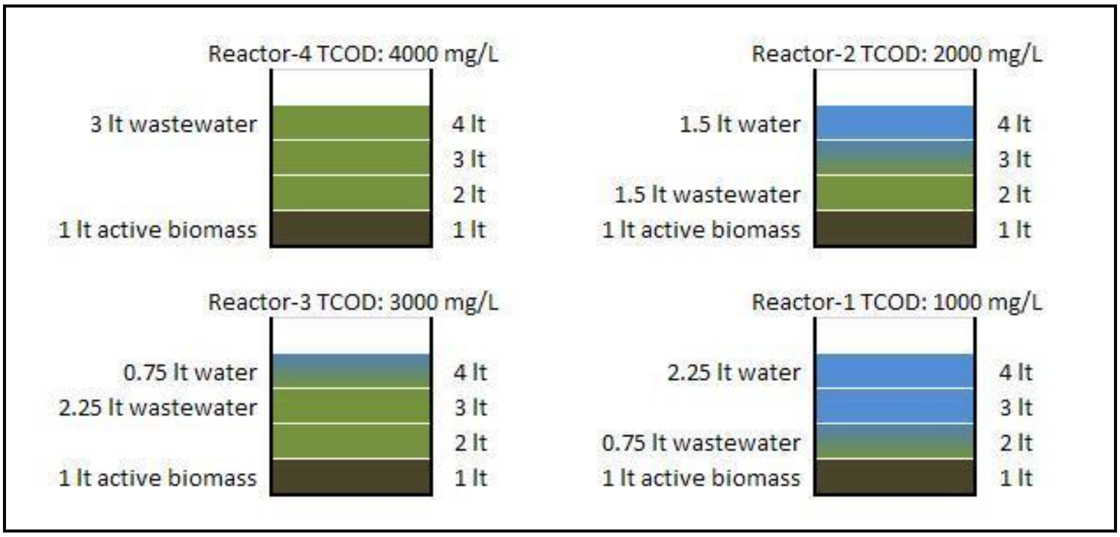

Figure 4.1: Reactor setup volumes and dilutions

Necessary dilutions were used throughout reactor feeding so that diverse influent COD concentrations could be formed for each reactor. Reactors were operated as fill & draw reactors under aerobic conditions with a minimum oxygen level of 2 mg/L. Aeration provided by the use of pressured air also secured necessary mixing conditions. Wastewater taken from equalization tank effluent was used to feed reactors. Reactors were fed and sludge was wasted in every two days based on the actual plant’s hydraulic retention time, which is 46 hours. Required dilutions were applied during feeding in order to ensure different influent COD concentrations for every reactor. Each reactor was left idle (without aeration) for two hours in order to provide settlement. After settling, each reactor was emptied until only 1 lt of reactor was left full and than the rest of 3 lt was filled with accordance to dilution ratios (see Figure 4.1). Sludge was wasted in every two days, with an amount of 500 ml from completely stirred phase. Additional nutrient supply was not found necessary and in times when needed pH adjustments were done using acid/base solutions (0.1 N HCl / NaOH).

Reactors were operated under these conditions for 26 days in order to provide necessary amount of time for acclimation. During acclimation period following parameters were analyzed; SS, VSS, TCOD, SCOD and pH.

4.3 Aerobic Stabilization Analysis

After acclimation period, reactors were operated in 2 liters volume, without feeding or sludge wasting, under aerobic conditions in order to promote conditions for aerobic sludge stabilization. During aerobic stabilization period following parameters were analyzed; SS, VSS, TOC, DOC, pH as well as DS and solids leaching analysis. Analyzed parameters are explained in detail in the next section. SS, VSS, TOC, DOC and pH analysis were carried out periodically based on a pre-determined schedule, throughout the whole aerobic stabilization analysis period, which is 30 days. Aerobic stabilization period was planned in order to provide sufficient time for achieving target stabilization levels and meeting minimum time required by ATV (2000) standards. Also periods over 30 days become economically unfeasible for applications, which was taken into account while determining stabilization period.

Sludge cake was formed in laboratory conditions in accordance with solids leaching analysis. Additional analysis on sludge cake sampled directly from the case study

WWTP was not carried out because wastewater in the case study WWTP undergoes both anaerobic and aerobic treatment and differs in characteristics. Sludge cake TOC, DOC and DS analysis were performed for three times indicating starting, middle and finishing dates. Additional nutrient supply or pH adjustments were not found necessary.

4.4 Sludge and Wastewater Parameters

Parameters analyzed during acclimation and stabilization periods as well as wastewater characterization are explained under this topic.

4.4.1 SS/VSS

SS and VSS samples were taken from completely mixed reactors and these two parameters were analyzed in accordance with Standard Methods (APHA, 2005).
Wastewater and sludge samples, were well-mixed than filtered through a weighed standard glass-fiber filter (1,5 µm Milipore AP 40) and the residue retained on the filter is dried to a constant weight at 103 to 105°C. The increase in weight of the filter represents the total suspended solids.
The residue from previous step is ignited to constant weight at 550°C. The remaining solids represent the fixed total, dissolved or suspended solids while the weight lost on ignition is the volatile solids.

4.4.2 TOC/DOC

TOC samples were taken from completely mixed reactors and also from sludge cake formed in laboratory conditions in accordance with solids leaching analysis. DOC samples taken from completely mixed reactors were further filtered through 0,45 µm membrane filters and also DOC parameter was analyzed for sludge cake eluates.
TOC and DOC analysis were carried out by Shimadzu TOC-5000A instrument which enables combustion in high temperatures and analysis were done according to Turkish Standards (TS 8195 EN 1484).

4.4.3 Formation of sludge cake in laboratory and solids leaching analysis

Samples taken from completely mixed reactors were centrifuged at 6.000 rpm for 10 minutes and sludge cake was formed. Solids leaching analysis were carried out in accordance with Turkish Standards (TS EN 12457-4), cake samples were mixed at room temperature (20 ± 5˚C), for 24 hours.

Total sludge cake sample obtained at the end of the experiment can be called original waste and when filtered through 0,45 µm (Milipore) membrane filters sample can be called eluate. According to solids leaching analysis method sludge sample is collected in order to include at least 90 g ± 5 g dry matter and water is added to provide 10 lt/kg ± %2 liquid to solid ratio (L/S). However, due to the limited amounts of sludge that can be prepared in laboratory, solids leaching analysis were carried out with lower weights and volumes. In calculation of results, dilution ratios were taken into account.

4.4.4 DS and pH

Dry solids/matter (DS) content of samples were determined in accordance with Turkish Standards (TS EN 12457).

Approximately, 0,5 g sludge cake sample was taken in an aluminum container and dried at 103-105^oC for 24 hours, later sample was weighed and dry matter content ratio is calculated as follows :

$$DS = 100*M_D/M_W \tag{4.1}$$

where;

DS : Dry matter content ratio, (%)

M_D : Mass of the dried sample, (kg)

M_W : Mass of undried sample, (kg) **(4.2)**

Samples for pH analysis were taken from completely mixed reactors, analysis were carried out by a calibrated pH meter in accordance with Standard Methods (APHA, 2005).

4.4.5 TCOD/SCOD

COD parameters were analyzed according to International Organization for Standardization method, ISO 6060. Method specified is applicable to water with a value between 30 mg/l and 700 mg/l. If the value exceeds 700 mg/l, the sample is diluted. Sample (1-10 ml) is transferred to the reaction flask and 5,0 ml of potassium dichromate solution is added as well as a few glass beads. Later, slowly 15 ml of silver sulfate-sulfuric acid is added and flasks are immediately attached to condenser in order to reflux for two hours. After cooled, condenser is washed down with distilled water and disconnected. Later, cooled to room temperature samples are titrated with standard ferrous ammonium sulfate (FAS) using two to three drops of ferroin indicator until color changes from blue-green to reddish brown that persists. In the same manner, blank(s) is refluxed and titrated containing the reagents and a volume of distilled water equal to that of sample. COD is given by the following expression:

$$COD \ (mg/l) = \frac{(a-b) * M * 8 * 1000}{V_{sample}} \quad \textbf{(4.3)}$$

a: FAS used for blank (ml)

b: FAS used for sample (ml)

M: Molarity of FAS, 8 is miliequivalent weight of oxygen and 1000 ml/lt for unit exchange

Soluble COD (SCOD) samples are filtered through 0,45 µm membrane filters and then put through the same procedure as explained above.

5. RESULTS AND DISCUSSION

5.1 Wastewater Characteristics

Wastewater samples were taken, from the brewery wastewater treatment plant equalization tank effluent, in three different dates; July 3rd, 17th and 31st. Results of conventional wastewater characterization studies carried out in the laboratory are presented in Table 5.1.

Table 5.1: Wastewater samples characterization

Parameters (Units)	July 3rd	July 17th	July 31st
SS (mg/L)	2550	1055	1803
VSS (mg/L)	1880	725	1303
VSS/SS (%)	74	69	72
TCOD (mg/L)	4834	4287	4561
SCOD (mg/L)	4061	3644	3763
SCOD/TCOD (%)	84	85	83
pH	6.15	5.75	5.45

When calculated on average basis, wastewater characterizations for all samples indicate values shown in (Table 5.2).

Table 5.2: Wastewater characterization (average)

Parameters (Units)	Average
SS (mg/L)	1800
VSS (mg/L)	1300
TCOD (mg/L)	4500
SCOD (mg/L)	3800
pH	5.80

These results are consistent with case study WWTP's wastewater characterization (see Chapter 3.4) with an exception of SS value which is caused mainly by different operations at the time of the sampling, allowing spent grains to come into the wastewater stream and increase solids input. Compared to the literature wastewater characteristics values (see Chapter 3.3) case study WWTP's organics and suspended solids concentrations values reflect a higher level. This is mainly because, literature values are based on European brewery facilities where, spent yeast is mostly not mixed with wastewater stream and treated, reused or disposed separately whereas in Turkey most of the brewery facilities such as the case study plant, do mix spent yeast into their wastewater and discharge them both into the WWTP. As offered in Table 5.3, an earlier study (Personal communications, 2009) on a comparable brewery designates that, influent wastewater characterization is significantly affected by yeast discharge.

Table 5.3: Effect of yeast discharge on wastewater characterization

Parameter	Unit	With yeast	Without yeast
SS	mg/L	508	235
VSS	mg/L	165	125
TCOD	mg/L	4425	1565
SCOD	mg/L	3195	1145

5.2 Acclimation Period

Reactors were operated for 26 days in order to provide necessary amount of time for acclimation. During acclimation period following parameters were analyzed; SS, VSS, TCOD, SCOD and pH. Monitoring of these parameters were started after a certain period of time (10-12 days) in order to allow starting conditions to become a little more balanced. The acclimation period was ended when results indicated a constant decline by narrower gaps as in a steady phase. This phase can be recognized by viewing last two results shown in Figure 5.1-Figure 5.12 for SS-VSS, TCOD and SCOD parameters for each reactor respectively. Different F/M ranges for all four reactors were observed during acclimation period; however, comparison F/M values for reactors were calculated based on theoretical influent TCOD values and steady phase SS results.

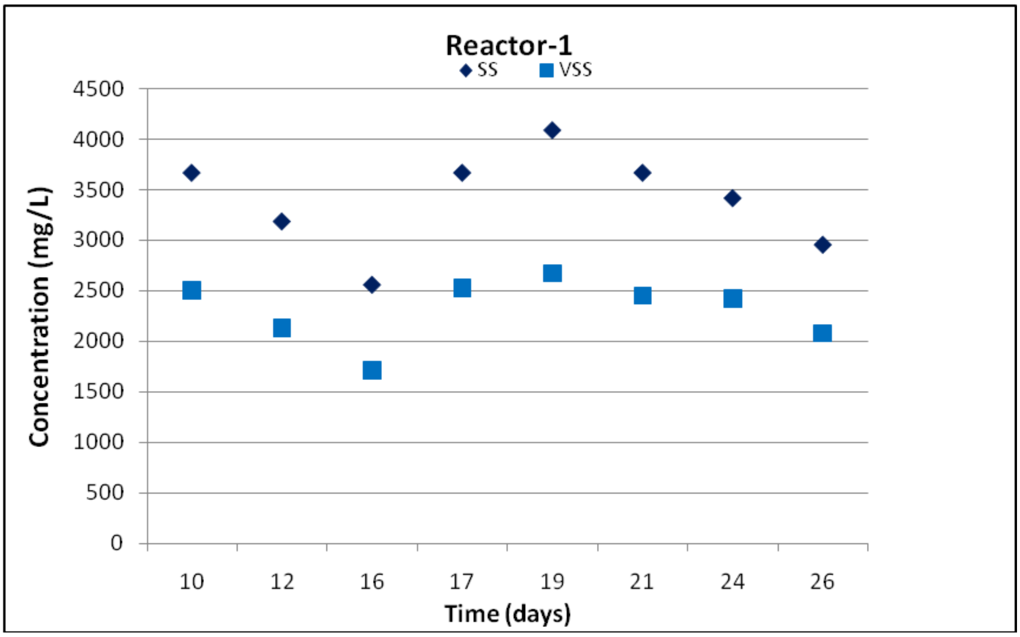

Figure 5.1: Acclimation period SS and VSS results for reactor-1

For all four reactors acclimation period SS-VSS results indicate sharp increases for at least one or two dates, which are related to reactor feeding. However, these increases, for reactor-1 day 17 and 19 values, are not consistent with TCOD-SCOD values and dates with increased values differ for every reactor, these findings indicate that SS-VSS increases are closely affected by settling regimes in reactors, which settling was observed to be very different (good or poor) for each reactor. VSS/SS ratios for reactor-1 are at start 68%, at end 70% and at average 68%.

Different F/M values for reactor-1 were observed during acclimation period; however, based on theoretical influent TCOD value and steady phase SS result for reactor-1, F/M ratio was calculated as 0.14 g COD/g SS.day.

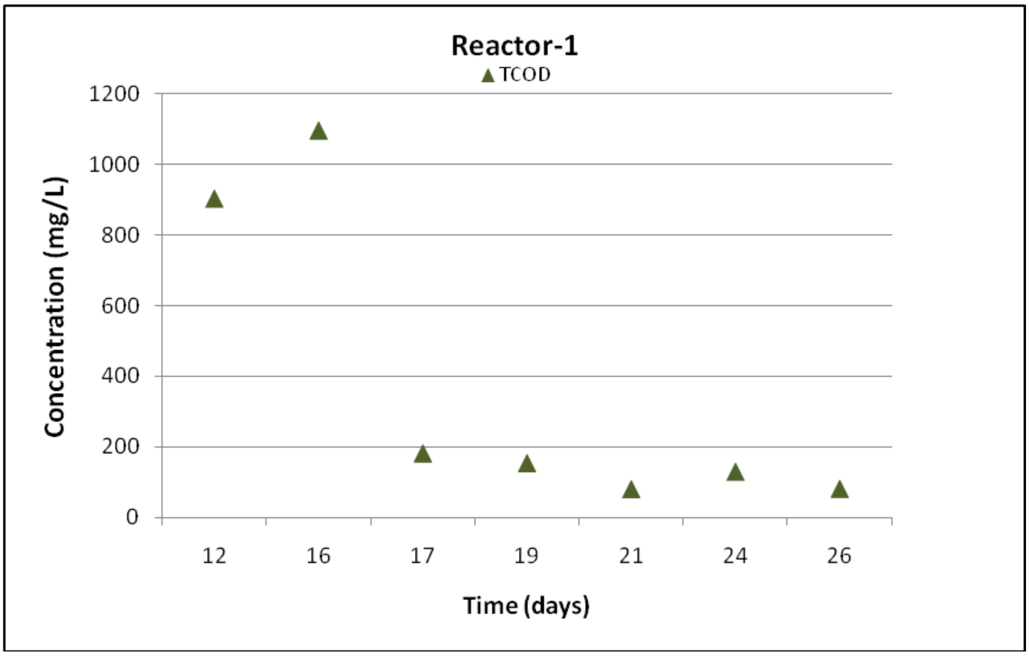

Figure 5.2: Acclimation period TCOD results for reactor-1

TCOD results for reactor-1 indicate that a steady phase in terms of total organic matter removal was attained after day 17.

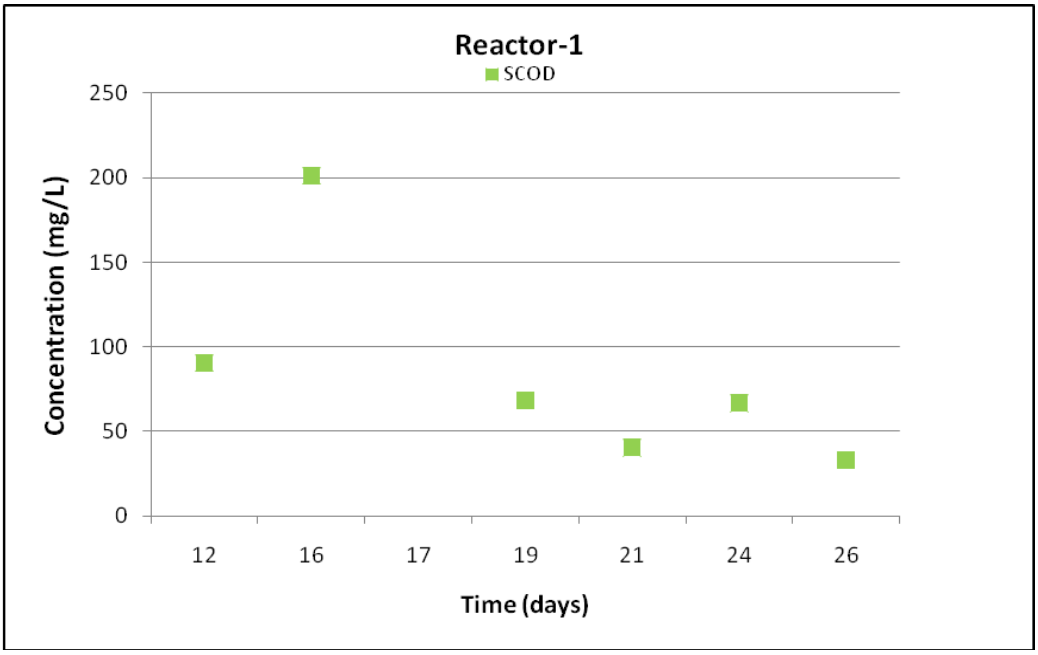

Figure 5.3: Acclimation period SCOD results for reactor-1

SCOD results for reactor-1 indicate that a steady phase in terms of soluble organic matter removal was attained after day 19. SCOD/TCOD ratios for reactor-1 are at start 10%, at end 74% and at average 47%.

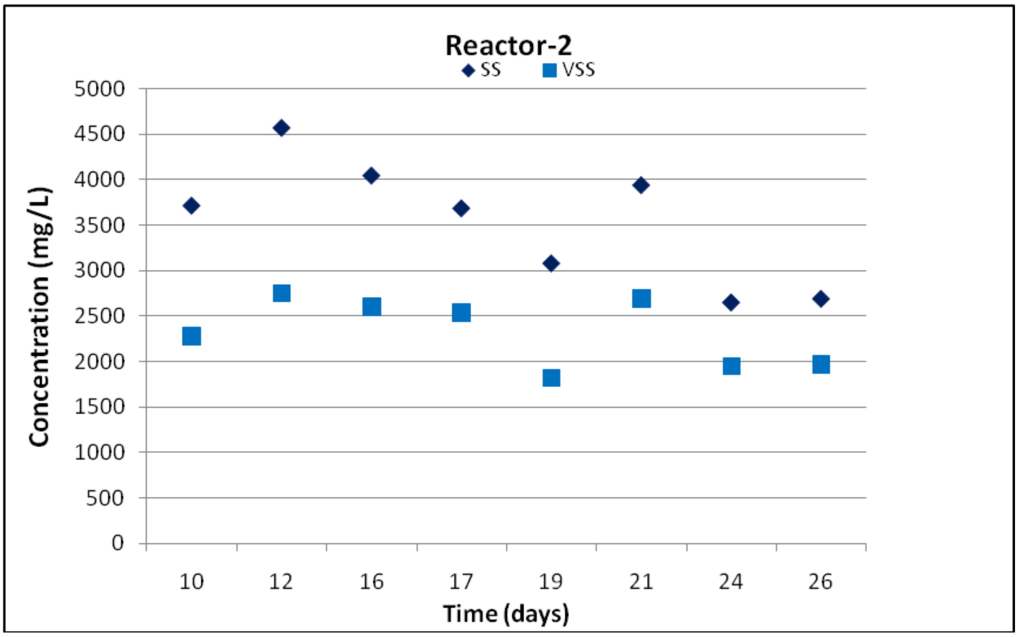

Figure 5.4: Acclimation period SS and VSS results for reactor-2

VSS/SS ratios for reactor-2 are at start 61%, at end 73% and at average 66%. For all four reactors acclimation period SS-VSS results indicate sharp increases for at least one or two dates, which are connected to reactor feeding dates. On the other hand, these increases, for reactor-2 day 12 and 21 values, are not consistent with TCOD-SCOD values and dates with increased values differ for every reactor, these findings point out that SS-VSS increases are closely affected by settling regimes in reactors, settling was observed to be good for some reactors whereas very poor for others.

Different F/M values for reactor-2 were observed during acclimation period; however, based on theoretical influent TCOD value and steady phase SS result for reactor-2, F/M ratio was calculated as 0.26 g COD/g SS.day.

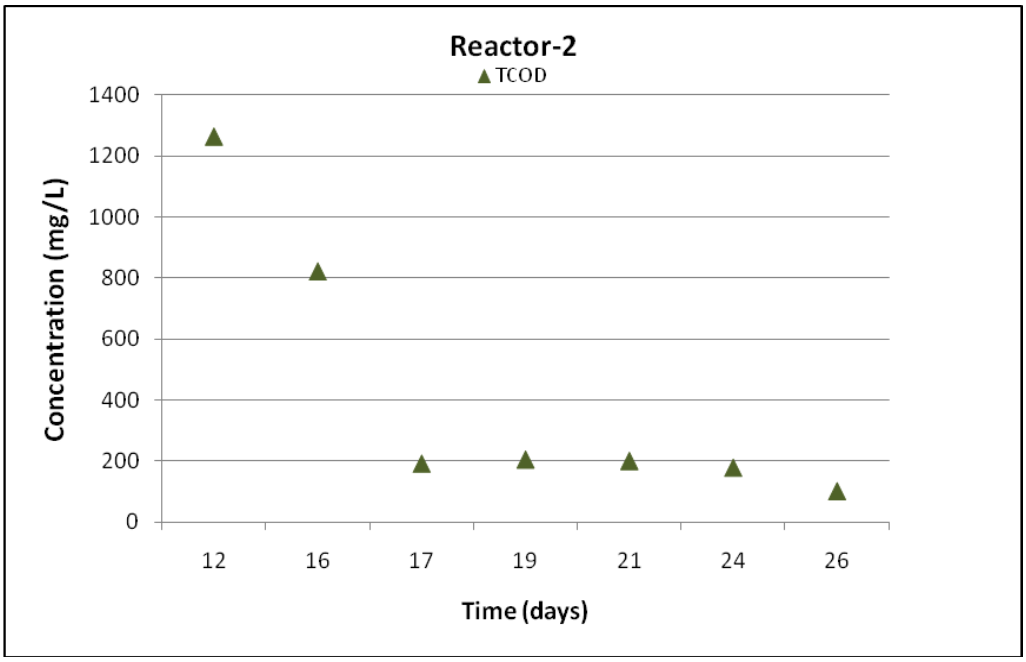

Figure 5.5: Acclimation period TCOD results for reactor-2

TCOD results for reactor-2 signify that a steady phase in terms of total organic matter removal was reached after day 17.

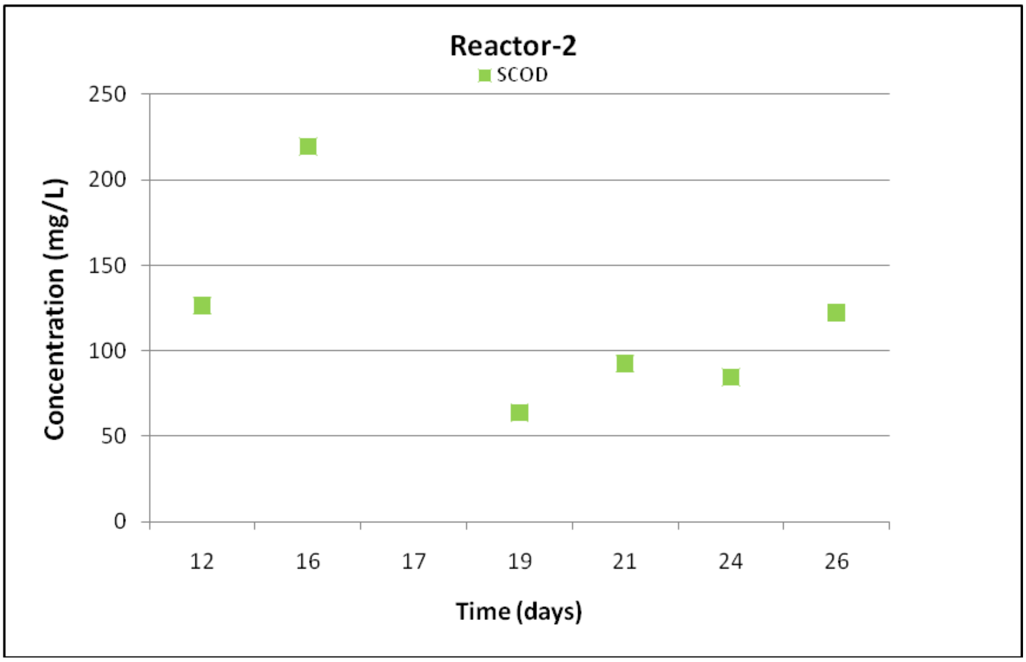

Figure 5.6: Acclimation period SCOD results for reactor-2

SCOD results for reactor-2 signify that a steady phase in terms of soluble organic matter removal was not reached at any time. SCOD/TCOD ratios for reactor-2 are at start 10%, at end 52% and at average 36%.

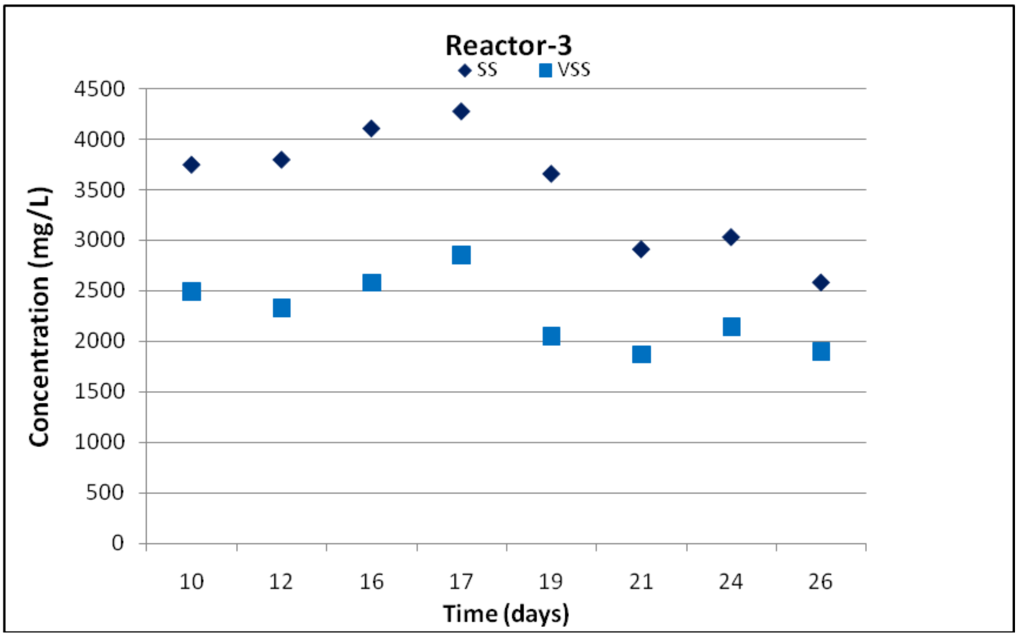

Figure 5.7: Acclimation period SS and VSS results for reactor-3

VSS/SS ratios for reactor-3 are at start 66%, at end 74% and at average 65%. Acclimation period SS-VSS results indicate sharp increases for at least one or two dates for all four reactors, which are linked to reactor feeding. Then again, these increases, for reactor-3 day 16 and 17 values, are not consistent with TCOD-SCOD values and dates with increased values differ for every reactor, these findings reveal that SS-VSS increases are closely affected by settling regimes in reactors, settling was observed to be taking place differently for each reactor.

Different F/M values for reactor-3 were observed during acclimation period; however, based on theoretical influent TCOD value and steady phase SS result for reactor-3, F/M ratio was calculated as 0.54 g COD/g SS.day.

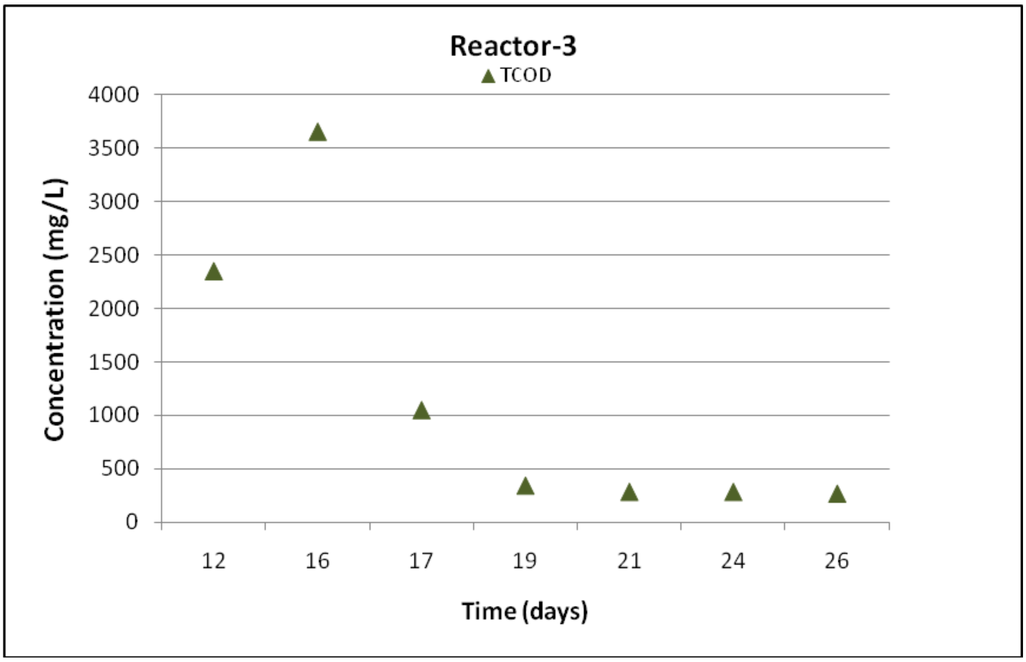

Figure 5.8: Acclimation period TCOD results for reactor-3

TCOD results for reactor-3 point toward a steady phase in terms of total organic matter removal was achieved after day 19.

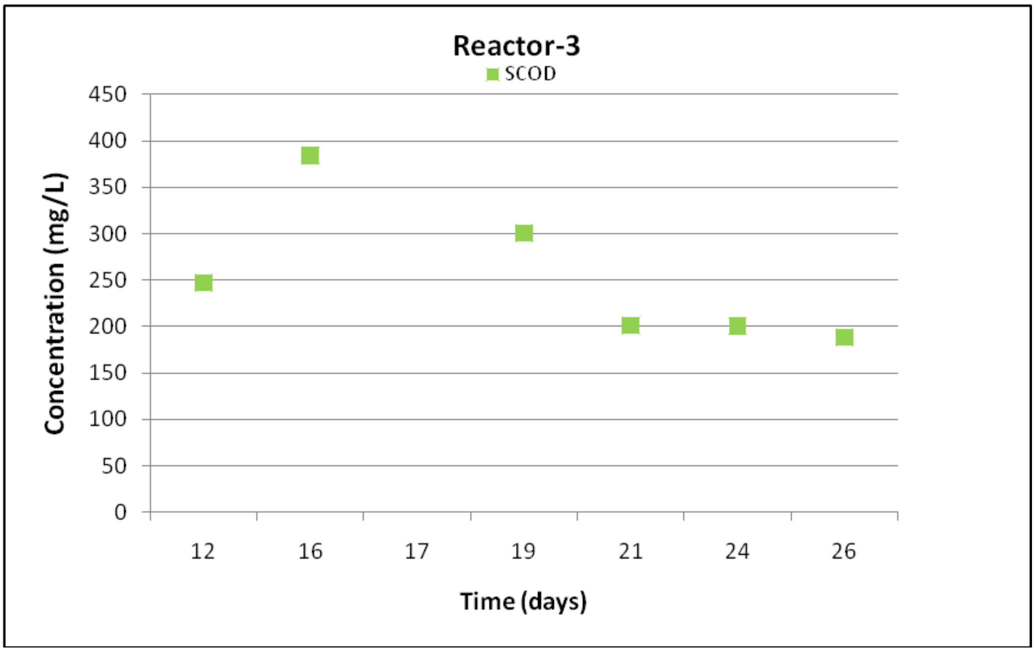

Figure 5.9: Acclimation period SCOD results for reactor-3

SCOD results for reactor-3 point toward that a steady phase in terms of soluble organic matter removal was attained after day 21. SCOD/TCOD ratios for reactor-3 are at start 11%, at end 71% and at average 54%.

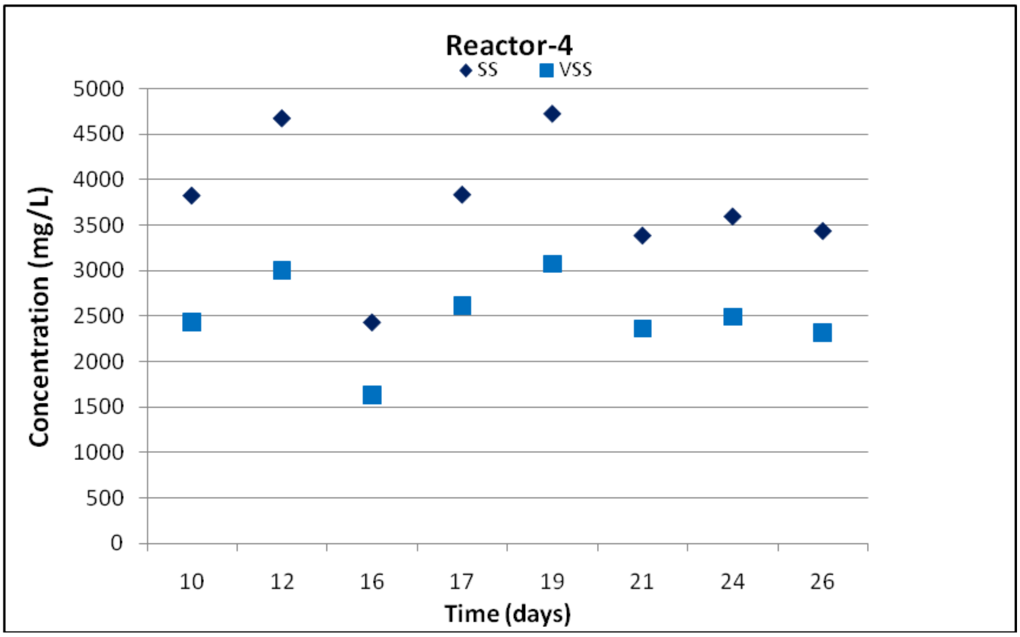

Figure 5.10: Acclimation period SS and VSS results for reactor-4

VSS/SS ratios for reactor-4 are at start 63%, at end 67% and at average 67%. Acclimation period SS-VSS results indicate sharp increases for at least one or two dates for all four reactors, which are associated to reactor feeding. Though, these increases, for reactor-4 day 12, 17 and 19 values, are not consistent with TCOD-SCOD values and dates with increased values differ for every reactor, these findings disclose that SS-VSS increases are closely affected by settling regimes in reactors, where for each reactor different settling qualities were observed.

Different F/M values for reactor-4 were observed during acclimation period; however, based on theoretical influent TCOD value and steady phase SS result for reactor-4, F/M ratio was calculated as 0.61 g COD/g SS.day.

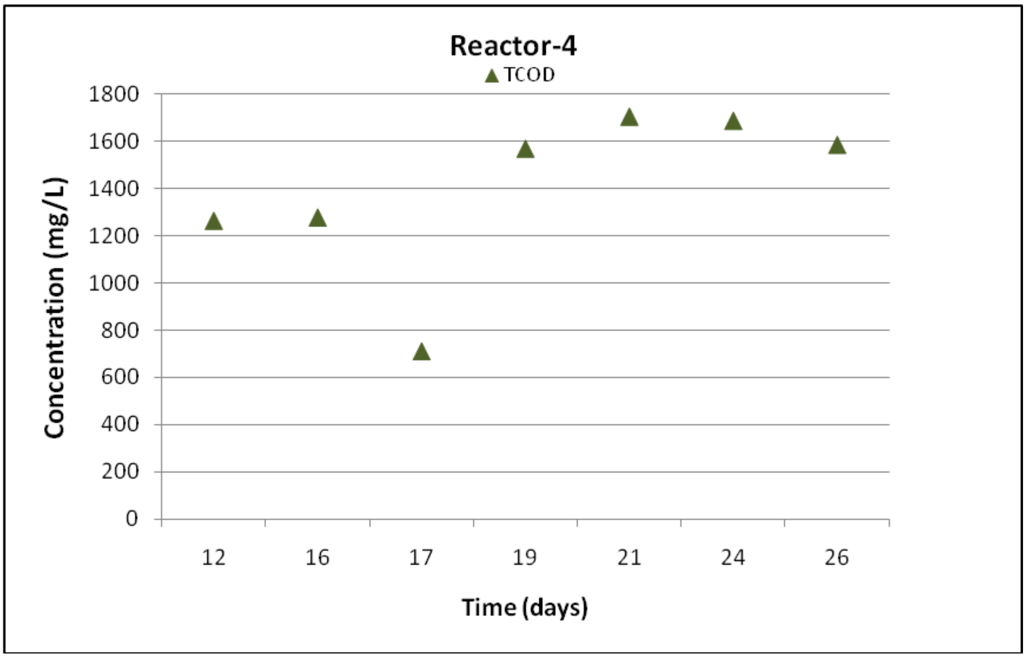

Figure 5.11: Acclimation period TCOD results for reactor-4

TCOD results for reactor-4 suggest that a steady phase in terms of total organic matter removal was reached after day 19. When compared to other reactors, reactor-4 indictaes higher TCOD values which is linked to feeding wastewater because for all other reactors feeding wastewater was diluted. However, an interference due to experimental methods is also a cause for these higher results which can only be observed for reactor-4 TCOD values but not for SCOD values.

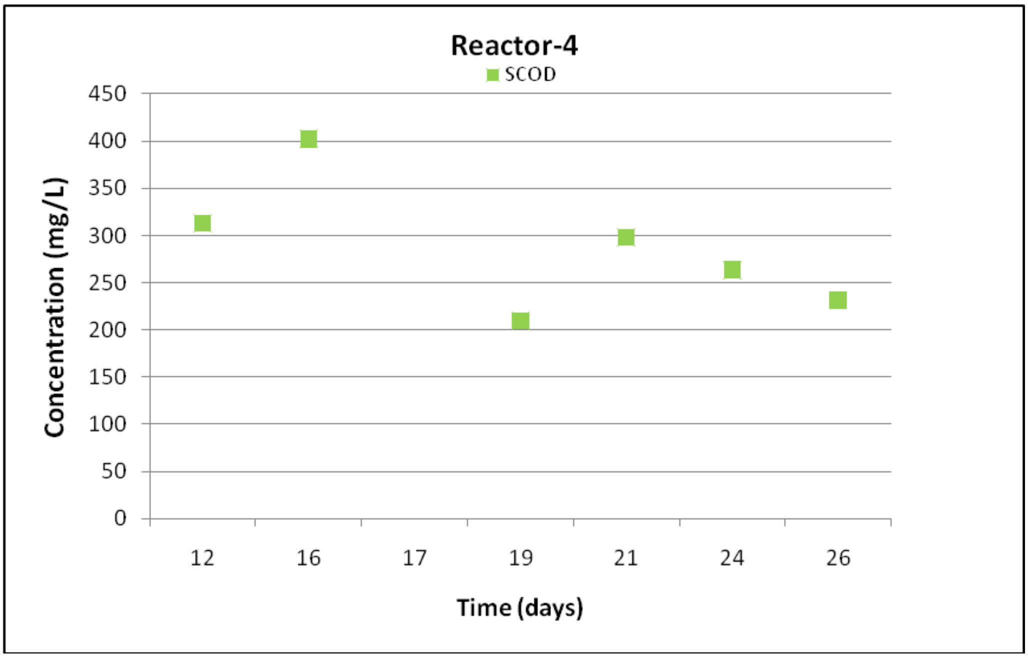

Figure 5.12: Acclimation period SCOD results for reactor-4

SCOD results for reactor-4 suggest that a steady phase in terms of soluble organic matter removal was not reached at any time.SCOD/TCOD ratios for reactor-4 are at start 25%, at end 15% and at average 20%.

Influent COD values were calculated by using feeding wastewater COD concentrations. COD removal rates were computed by taking into account both influent COD values and SCOD concentrations as effluent COD values. On average basis, COD removal rates are found to be 90% for reactor-1, 94% for reactor-2, 90% for reactor-3 and 92% for reactor-4.

In addition, variations of pH values for all reactors are shown in Figure 5.13, as can be seen pH values in all reactors are confined within the range of pH 8-9.

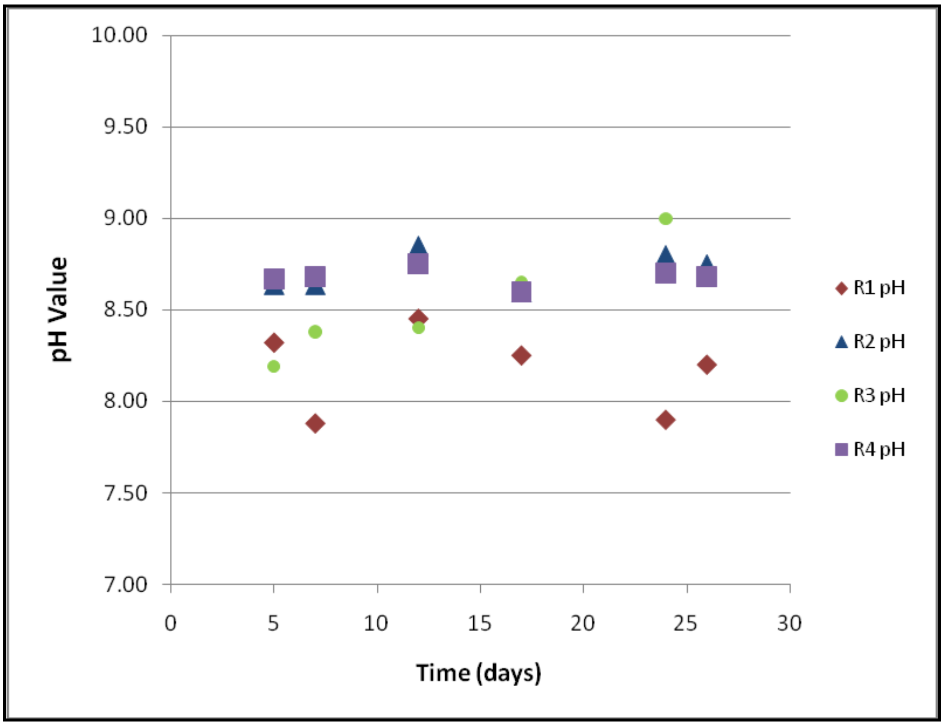

Figure 5.13: Acclimation period pH results

During acclimation period an additional 5th reactor was operated in order to asses soluble inert fraction of COD. This additional reactor was filled with same brewery wastewater and activated sludge samples, than was continuously aerated without any further feeding or sludge removal. Analysis were started at 12th day and operation of this reactor was halted when a fix value (≈100 mg/L) for inert SCOD was acquired repeatedly (Figure 5.14).

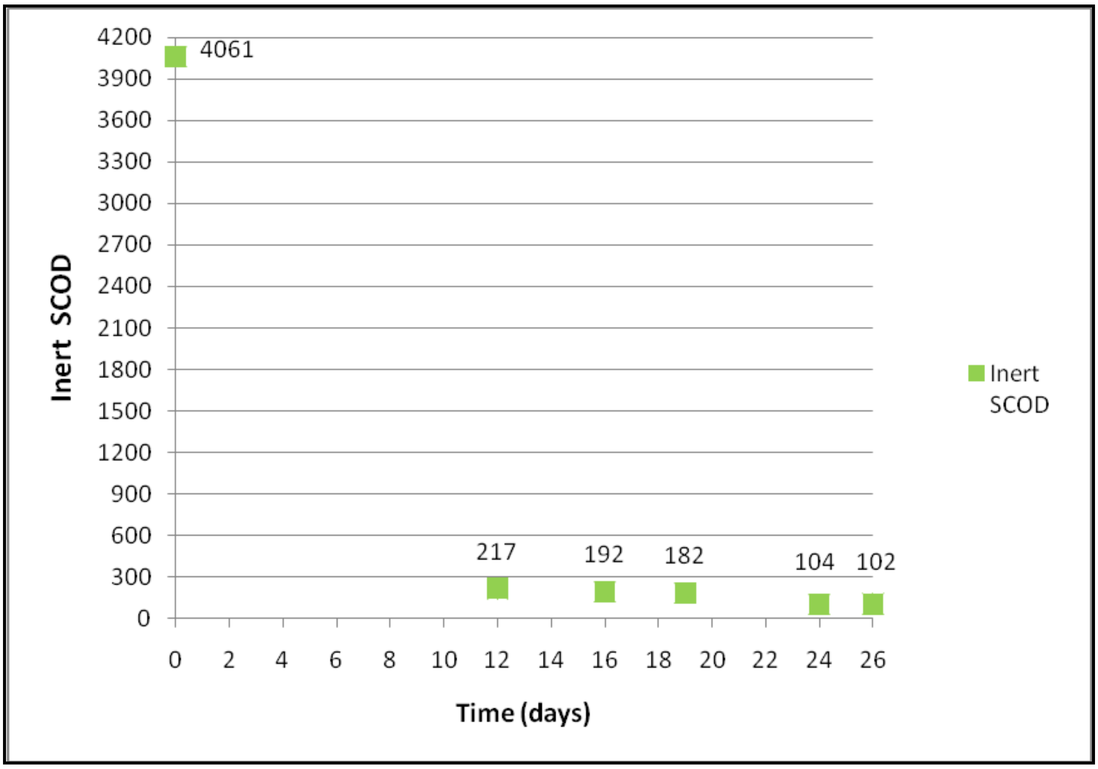

Figure 5.14: Inert SCOD analysis

5.3 Aerobic Stabilization Results

After acclimation period has ended, reactors were operated in a fixed volume of 2 liters under aerobic conditions with no feeding, with the purpose of promoting circumstances for aerobic sludge stabilization. Aerobic stabilization period was planned as a 30 day long phase in order to provide sufficient time for achieving target stabilization levels. Periods over 30 days indicate economically unfeasible applications whereas periods under 20 days signify insufficient retention times for stabilization. During aerobic stabilization period following parameters were analyzed; SS, VSS, TOC, DOC, pH as well as DS and solids leaching analysis. During aerobic stabilization period, SS, VSS and TOC parameters for all reactors are shown over time in Figure 5.15-Figure 5.18.

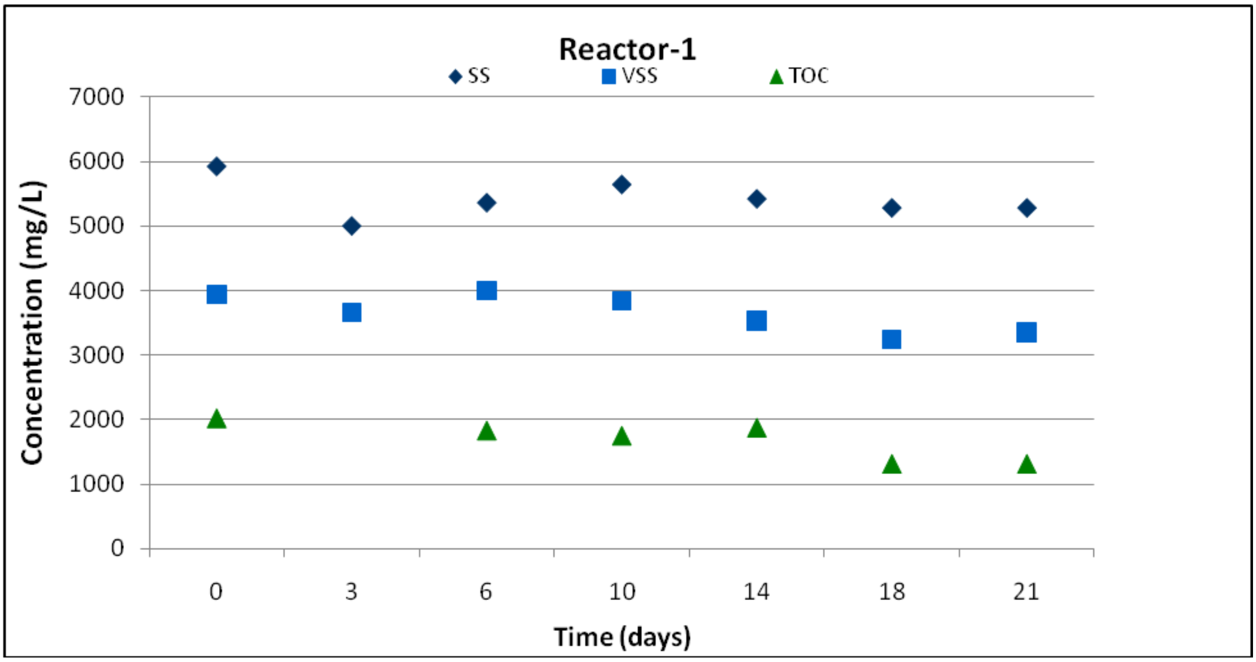

Figure 5.15: Aerobic stabilization period, SS, VSS and TOC results for reactor-1

For reactor-1, steady results were achieved at 21 days therefore removal rates were calculated based on results for 21st day. Results for days 21 to 30 were not used because they either indicated steady or higher values. SS and VSS removal rates are computed for reactor-1 as 11% and 15%. VSS removal rates were found to be in order with literature values (Tchobanoglous, 2003). VSS/SS ratios at the beginning (day 0) and at the end (day 21) are found to be 0.67 and 0.63 for reactor-1.

For reactor-1, comparable steady TOC results were gathered at days 18 and 21. Starting (day 0) TOC value is determined as 2027 mg/L, with a removal rate of 35%, final (day 21) value is reduced to 1316 mg/L. When analyzed, for all four reactors aerobic stabilization in-reactors TOC results indicate that most of the biodegradable organic matter is consumed, until a certain level (≈1000 mgTOC/L) is reached, where residue is mostly inert.

Aerobic stabilization results signify a firm ratio between TOC and SS values, this proportion (TOC/SS) for reactor-1 is found as 31% at average, changing within a range of 5%. This close relation also indicates that, sludge cake TOC levels will not change dramatically.

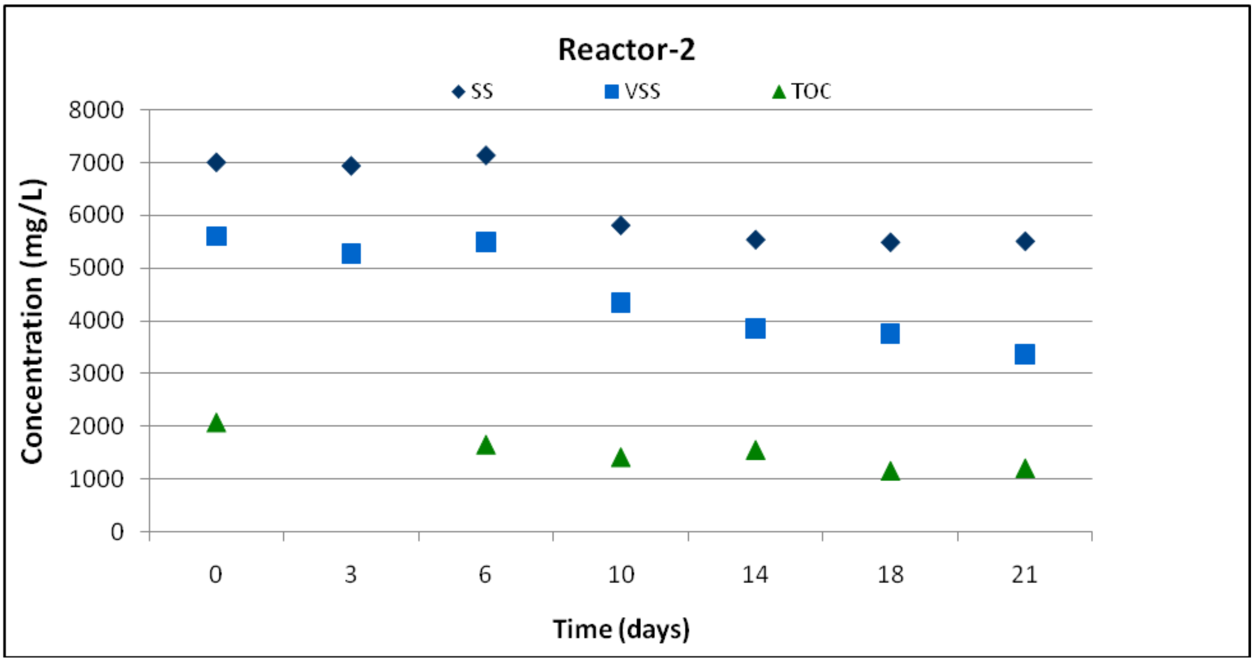

Figure 5.16: Aerobic stabilization period, SS, VSS and TOC results for reactor-2

For reactor-2, steady results were achieved after 21 days therefore removal rates were calculated based on results for 21st day. Results for days 21 to 30 were not used because they either indicated steady or higher values. SS and VSS removal rates are computed for reactor-2 as 21% and 40%. VSS removal rates were found to be in order with literature values (Tchobanoglous, 2003). VSS/SS ratios at the beginning (day 0) and at the end (day 21) are found to be 0.80 and 0.61 for reactor-2.

For reactor-2, comparable steady TOC results were gathered at days 18 and 21. Starting TOC value is determined as 2073 mg/L, with a removal rate of 42%, final value is reduced to 1200 mg/L. When analyzed, for all four reactors aerobic stabilization in-reactors TOC results indicate that most of the biodegradable organic matter is consumed, until a certain level (≈1000 mgTOC/L) is reached, where residue is mostly inert.

Aerobic stabilization results signify a firm ratio between TOC and SS values, this proportion (TOC/SS) for reactor-2 is found as 25% at average, changing within a range of 5%. This close relation also points out that, sludge cake TOC levels will not change noticeably.

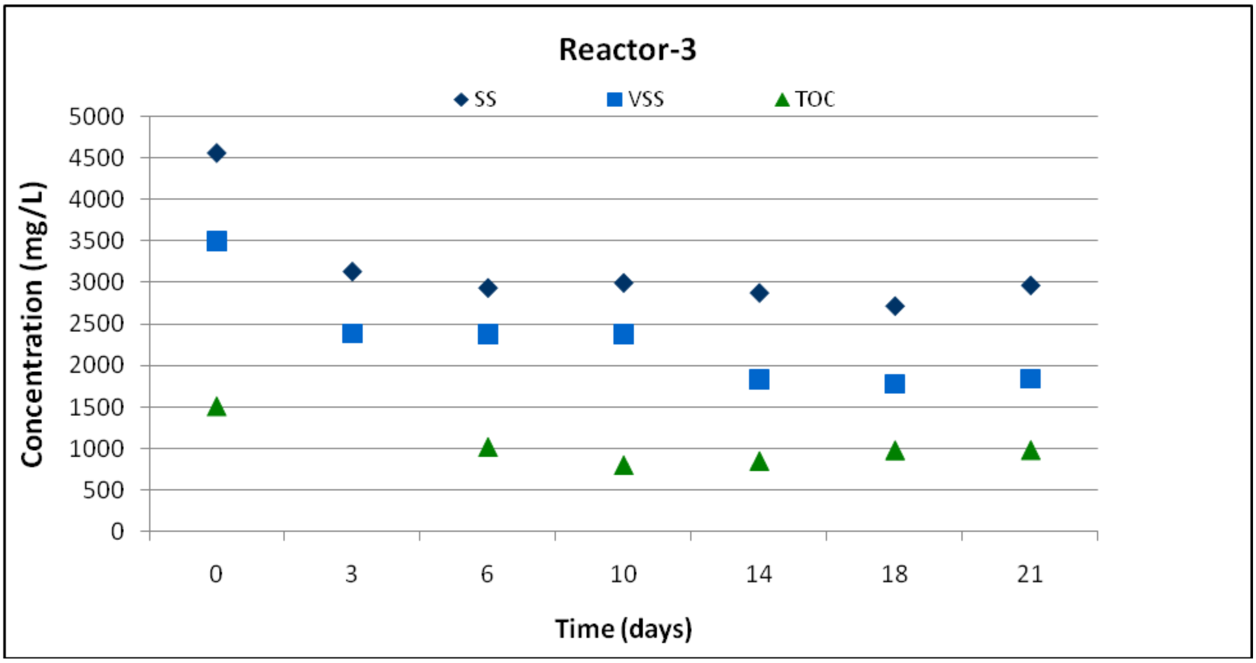

Figure 5.17: Aerobic stabilization period, SS, VSS and TOC results for reactor-3

For reactor-3, steady results were achieved after 21 days therefore removal rates were calculated based on results for 21st day. Results for days 21 to 30 were not used because they either indicated steady or higher values. SS and VSS removal rates are computed for reactor-3 as 35% and 47%. VSS removal rates were found to be in order with literature values (Tchobanoglous, 2003). VSS/SS ratios at the beginning (day 0) and at the end (day 21) are found to be 0.77 and 0.62 for reactor-3.

For reactor-3, comparable steady TOC results were gathered at days 14, 18 and 21. Starting TOC value is determined as 1514 mg/L, with a removal rate of 35%, final value is reduced to 983 mg/L. When analyzed, for all four reactors aerobic stabilization in-reactors TOC results indicate that most of the biodegradable organic matter is consumed, until a certain level (≈1000 mgTOC/L) is reached, where residue is mostly inert.

Aerobic stabilization results signify a firm ratio between TOC and SS values, this proportion (TOC/SS) for reactor-3 is found as 32% at average, changing within a range of 5%. This close relation also specifies that, sludge cake TOC levels will not change noticeably.

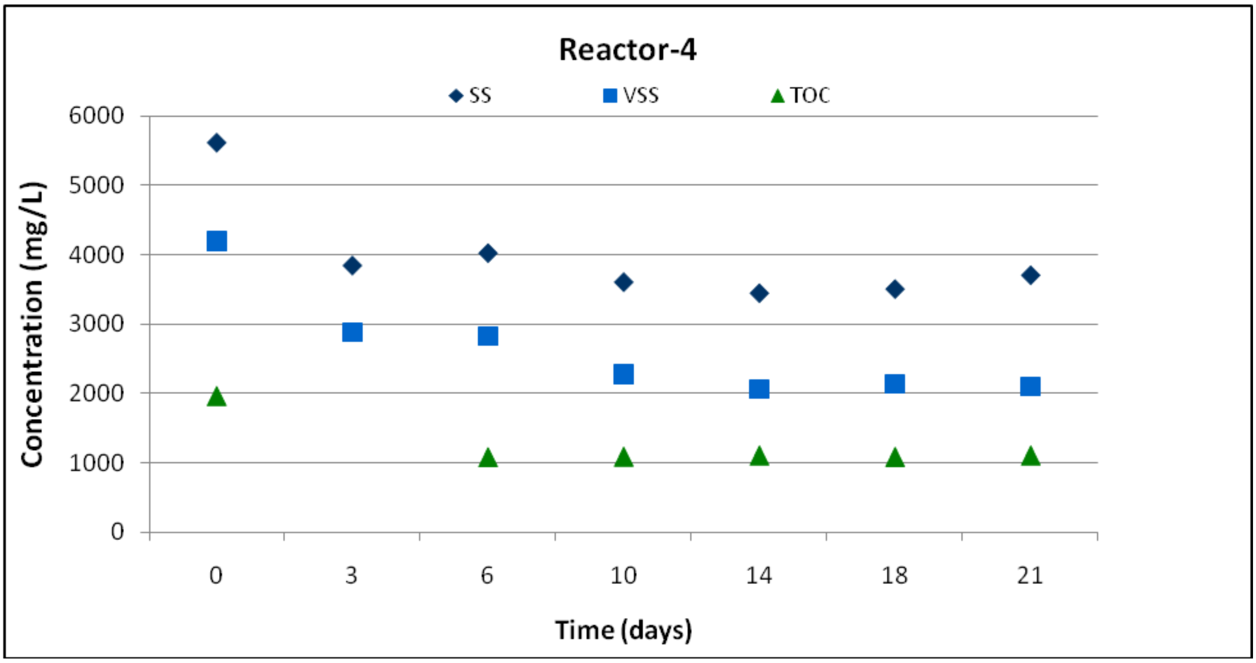

Figure 5.18: Aerobic stabilization period, SS, VSS and TOC results for reactor-4

For reactor-4, steady results were achieved after 21 days therefore removal rates were calculated based on results for 21st day. Results for days 21 to 30 were not used because they either indicated steady or higher values. SS and VSS removal rates are computed for reactor-4 as 34% and 50%. VSS removal rates were found to be in order with literature values (Tchobanoglous, 2003). VSS/SS ratios at the beginning (day 0) and at the end (day 21) are found to be 0.75 and 0.57 for reactor-4.

For reactor-4, comparable steady TOC results were gathered at days 6, 10, 14, 18 and 21. Starting TOC value is determined as 1956 mg/L, with a removal rate of 43%, final value is reduced to 1110 mg/L. When analyzed, for all four reactors aerobic stabilization in-reactors TOC results indicate that most of the biodegradable organic matter is consumed, until a certain level (≈1000 mgTOC/L) is reached, where residue is mostly inert.

Aerobic stabilization results signify a firm ratio between TOC and SS values, this proportion (TOC/SS) for reactor-4 is found as 31% at average, changing within a range of 4%. This close relation also shows that, sludge cake TOC levels will not change significantly.

TOC and DOC analysis were carried out in order to provide data on sludge stabilization rates and levels. Results for DOC parameter are given in Figure 5.19-Figure 5.22.

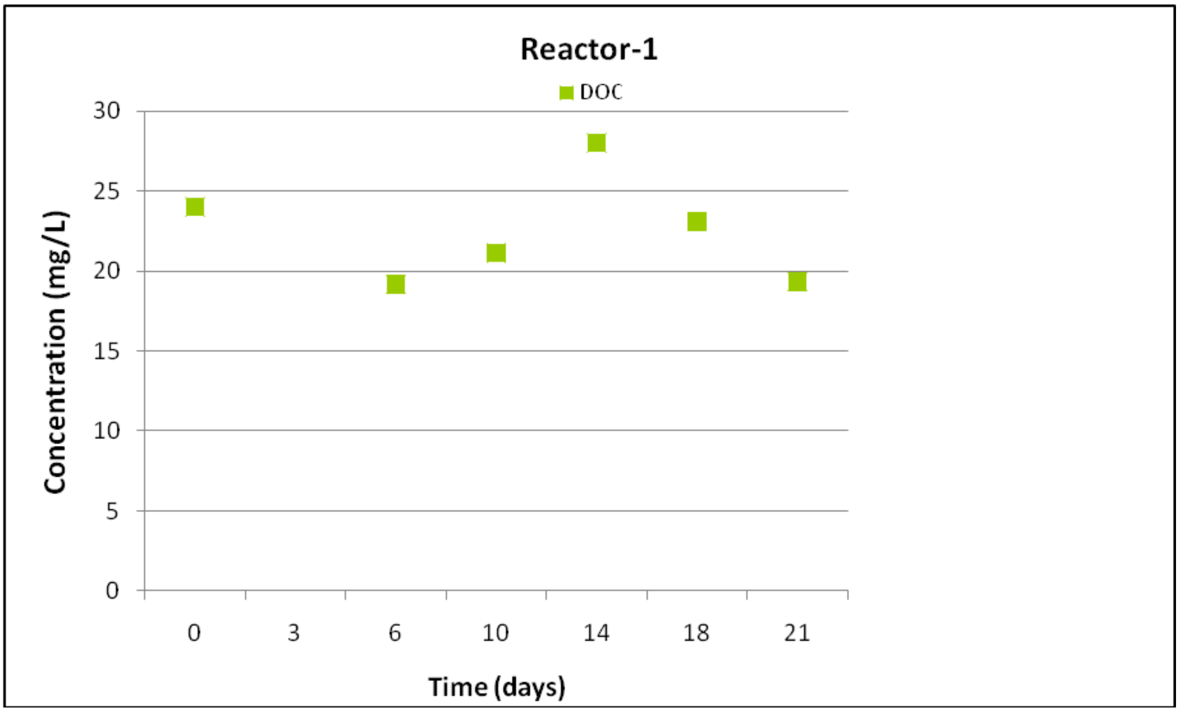

Figure 5.19: Aerobic stabilization period, DOC results for reactor-1

As for DOC results, reactor-1, starting DOC value is determined as 24 mg/L, with a removal rate of 20%, final value is reduced to 19 mg/L. At days 10 and 14, DOC level showed a rise and than a fall. This trend can be explained by formation of non-biodegradable microbial products during aerobic stabilization period. When compared to time before this formation, steady DOC result was gathered at day 21, thus removal rate was calculated based on result for 21st day. As can be seen, trend between last three results indicate that in-reactor DOC levels decrease in a linear fashion.

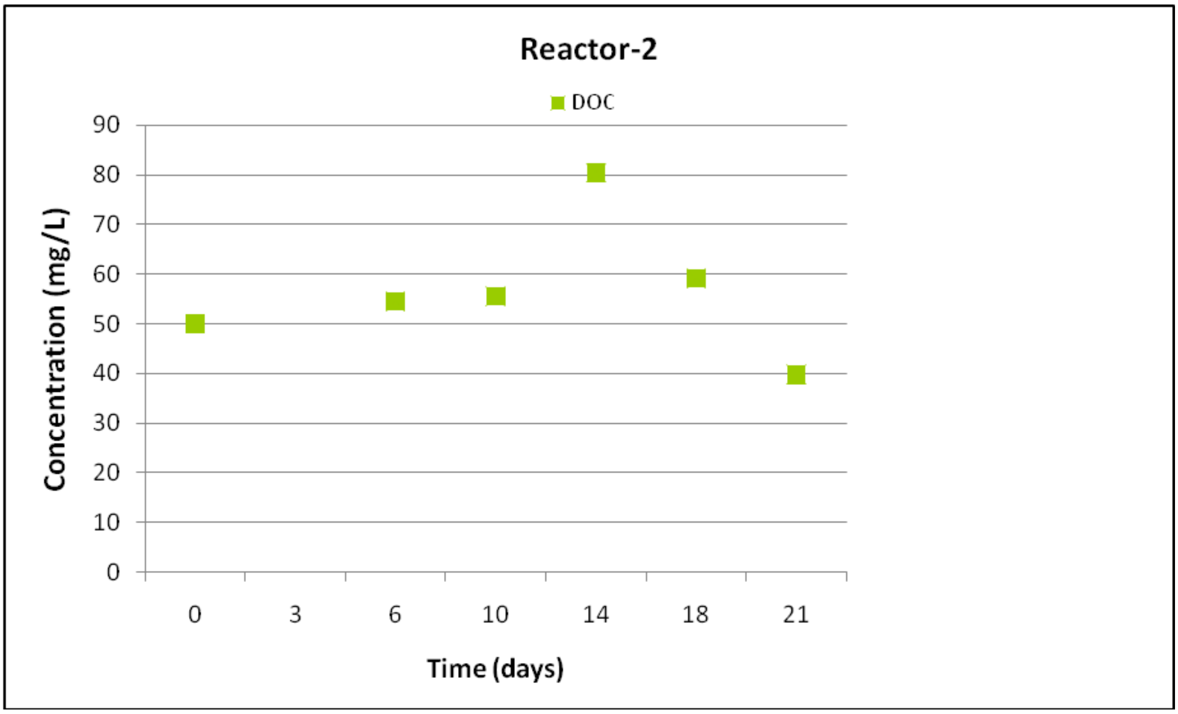

Figure 5.20: Aerobic stabilization period, DOC results for reactor-2

As for DOC results, reactor-2, starting DOC value is determined as 50 mg/L, with a removal rate of 20%, final value is reduced to 40 mg/L. At day 14, DOC level showed a rise and than a fall. This trend can be explained by formation of non-biodegradable microbial products during aerobic stabilization period. When compared to time before this formation, decreased DOC result was gathered at day 21, thus removal rate were calculated based on result for 21st day. As can be seen, trend between last three results indicate that in-reactor DOC levels decrease in a linear manner.

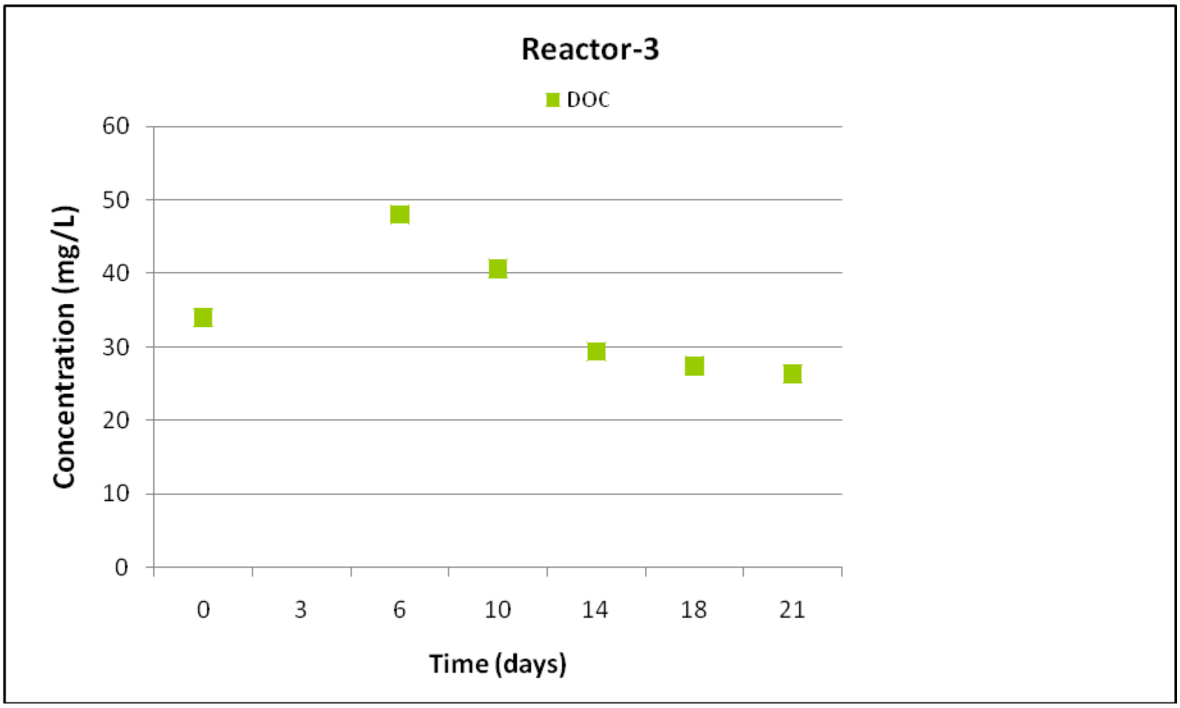

Figure 5.21: Aerobic stabilization period, DOC results for reactor-3

As for DOC results, reactor-3, starting DOC value is determined as 34 mg/L, with a removal rate of 23%, final value is reduced to 26 mg/L. At day 6, DOC level showed a rise and than a fall. This trend can be explained by formation of non-biodegradable microbial products during aerobic stabilization period. When compared to time before this formation, decreased and steady DOC results were gathered at days 18 and 21, thus removal rate was calculated based on result for 21st day. As can be seen, trend between last three results indicate that in-reactor DOC levels decrease in a steady way.

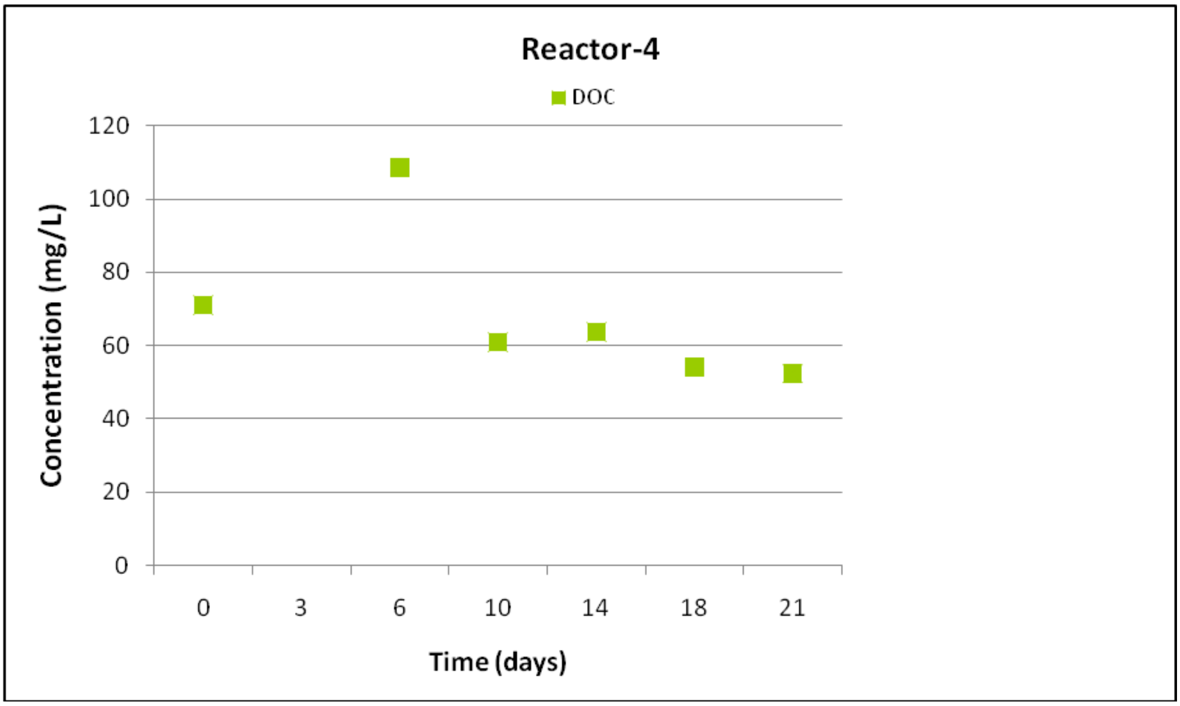

Figure 5.22: Aerobic stabilization period, DOC results for reactor-4

As for DOC results, reactor-4, starting DOC value is determined as 71 mg/L, with a removal rate of 26%, final value is reduced to 52 mg/L. At day 6, DOC level showed a rise and than a fall. This trend can be explained by formation of non-biodegradable microbial products during aerobic stabilization period. When compared to time before this formation, decreased and steady DOC results were gathered at days 18 and 21, thus removal rates were calculated based on results for 21st day.

Aerobic stabilization overview based on reactors removal rates is presented in Table 5.4.

Table 5.4: Aerobic stabilization general overview (in reactors)

	Removal rate (%)			
	SS	**VSS**	**TOC**	**DOC**
Reactor-1	11%	15%	35%	20%
Reactor-2	21%	40%	42%	20%
Reactor-3	35%	47%	35%	23%
Reactor-4	34%	50%	43%	26%

In order to investigate stabilized sludges' legal compatibility and landfilling possibility in reference to Regulation on the Control of Hazardous Waste (Date: 14/03/2005 and No: 25755) Annex-11A, sludge cakes were formed at certain times (day 0, 15 and 30) and these cakes were later taken into solids leaching analysis.

According to solids leaching analysis (TS EN 12457-4) dry solids contents of sludge cakes are determined and presented in Table 5.5.

Table 5.5: Dry solids contents for sludge cake

Time / Reactor	Dry Solids (%)		
	Day 0	**Day 15**	**Day 30**
Reactor-1	6.7%	5.6%	5.2%
Reactor-2	8.0%	5.3%	5.1%
Reactor-3	6.7%	4.5%	4.5%
Reactor-4	9.7%	5.5%	6.5%

Results for TOC and DOC parameters in sludge cakes are presented over time in Figure 5.23-Figure 5.30 for reactor-1, reactor-2, reactor-3 and reactor-4 respectively.

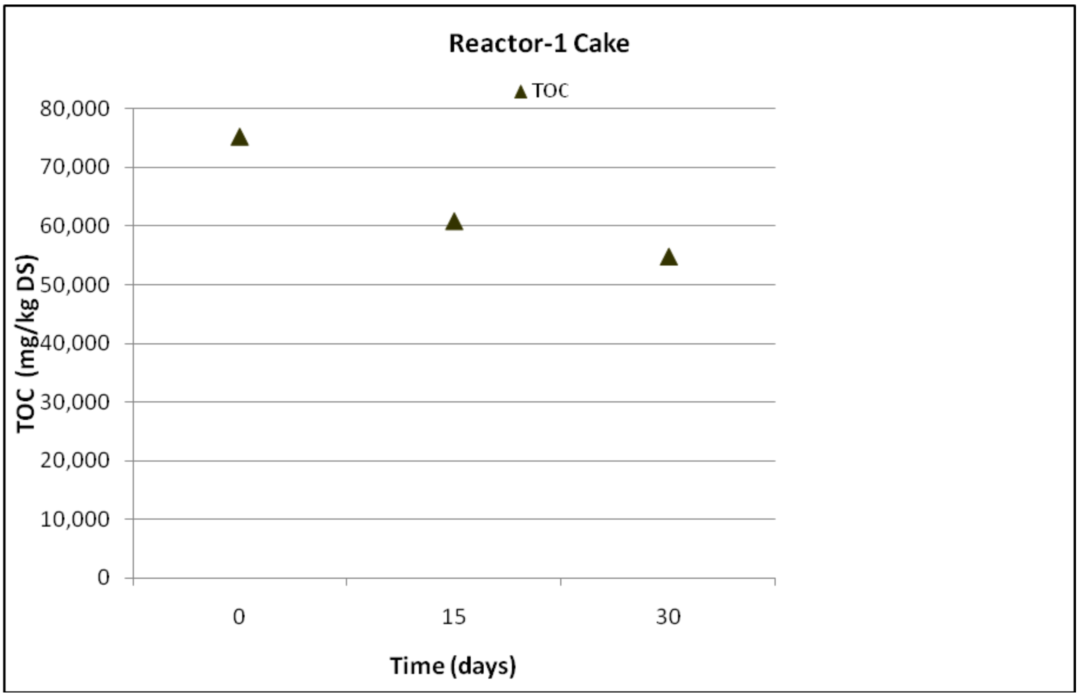

Figure 5.23: Sludge cake analysis TOC results for reactor-1

Limited TOC reduction, 27%, was observed for reactor 1. Looking back to aerobic stabilization in-reactors results, it can be seen that a solid ratio between TOC and SS values (TOC/SS: 31% +/- 5%) for reactor-1 was found which demonstrates that, sludge cake TOC levels will not change considerably.

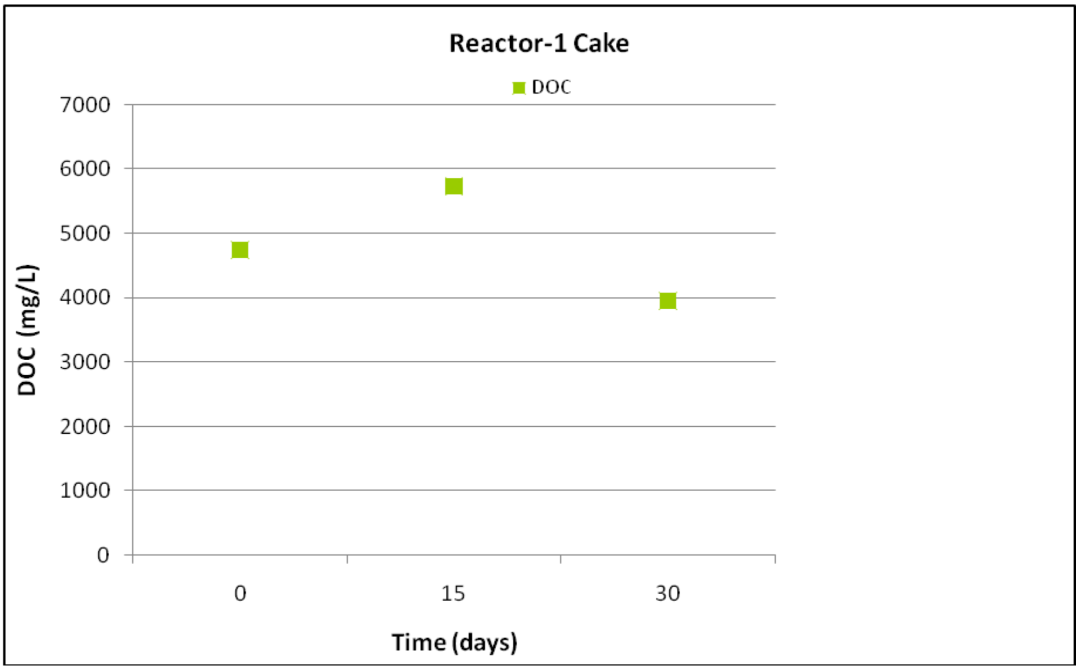

Figure 5.24: Sludge cake analysis DOC results for reactor-1

Limited DOC removal rate was monitored as 17% for reactor-1. Mid-point (day 15) increase for reactor-1 sludge cake DOC value, is considered to be caused by experimental method. Related method (TS 8195 EN 1484) states margin of error as up to 20%. This error might be the reason for such low removal rate.

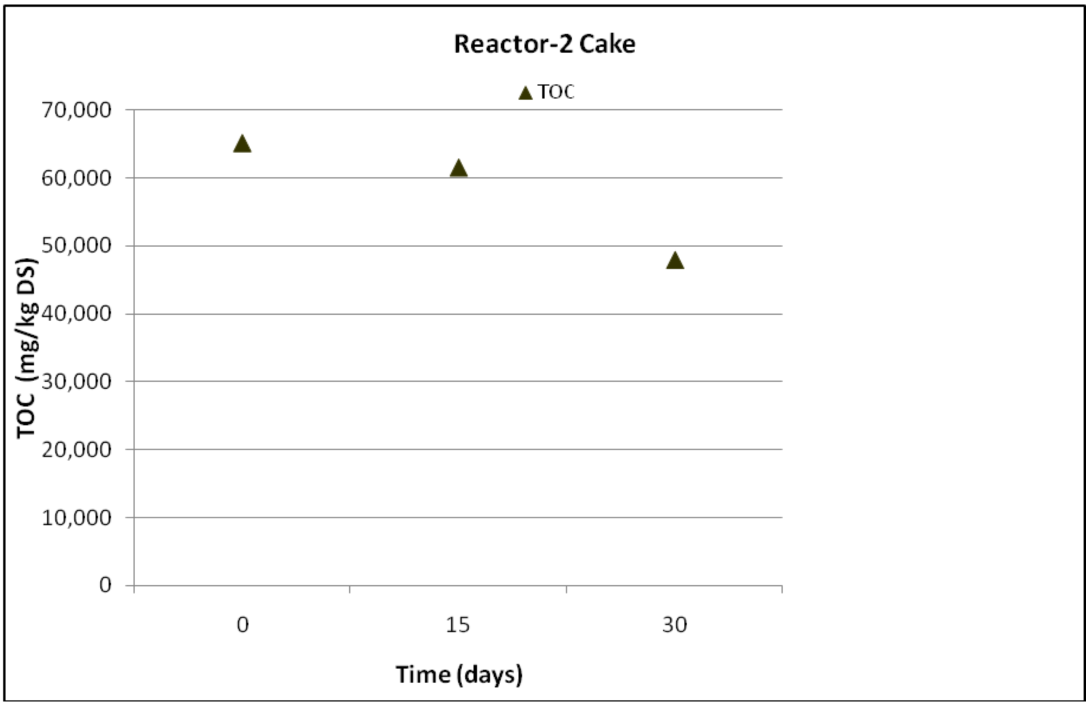

Figure 5.25: Sludge cake analysis TOC results for reactor-2

Limited TOC reduction, 26%, was observed for reactor 2. Analyzing aerobic stabilization in-reactors results, it can be seen that a solid ratio between TOC and SS values (TOC/SS: 25% +/- 5%) for reactor-2 was found which reveals that, sludge cake TOC levels will not alter noticeably.

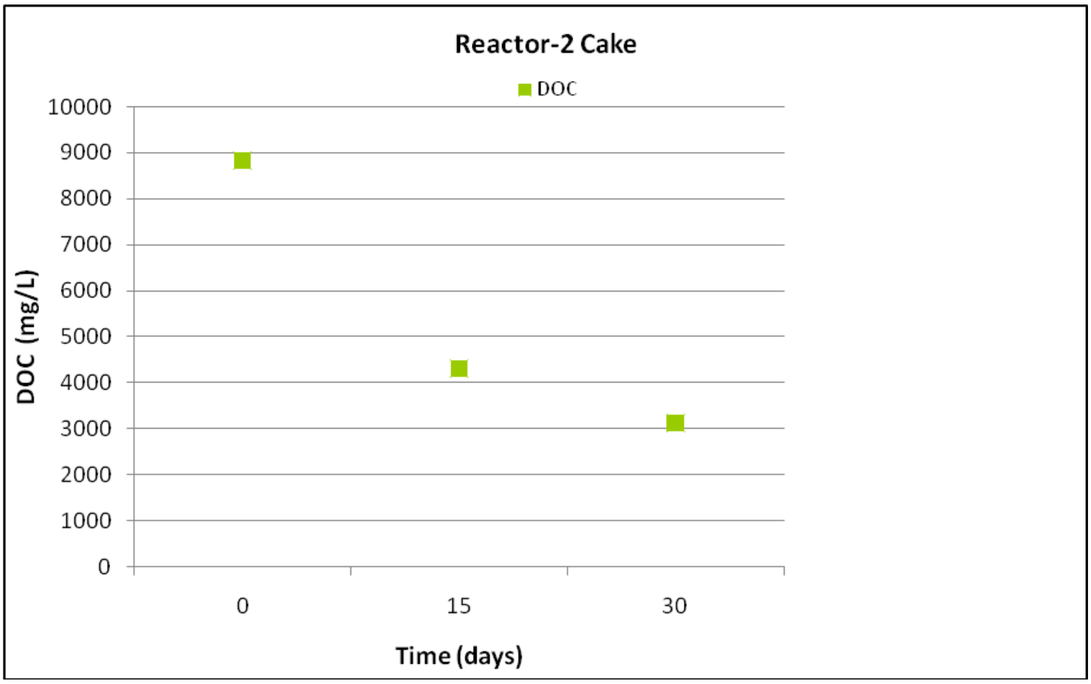

Figure 5.26: Sludge cake analysis DOC results for reactor-2

An average DOC removal rate was monitored as 65% for reactor-2. Unlike reactor-1 and reactor-3, no increase was observed within reactor-2 sludge cake DOC values. Therefore, when compared to reactor-1 and reactor-3, margin of error for this analysis is considered to be smaller and obtained results are regarded as more reliable.

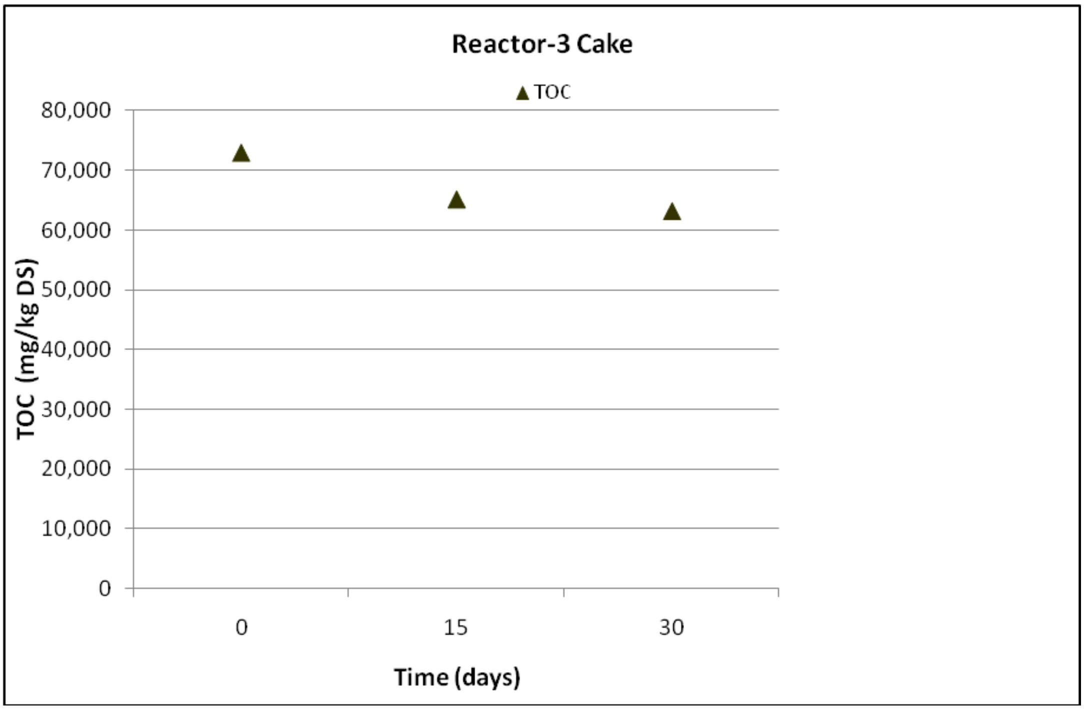

Figure 5.27: Sludge cake analysis TOC results for reactor-3

Very limited TOC reduction, 13%, was observed for reactor 3. Examining aerobic stabilization in-reactors results, it can be seen that a solid ratio between TOC and SS values (TOC/SS: 32% +/- 5%) for reactor-3 was found which discloses that, sludge cake TOC levels will not vary distinctly.

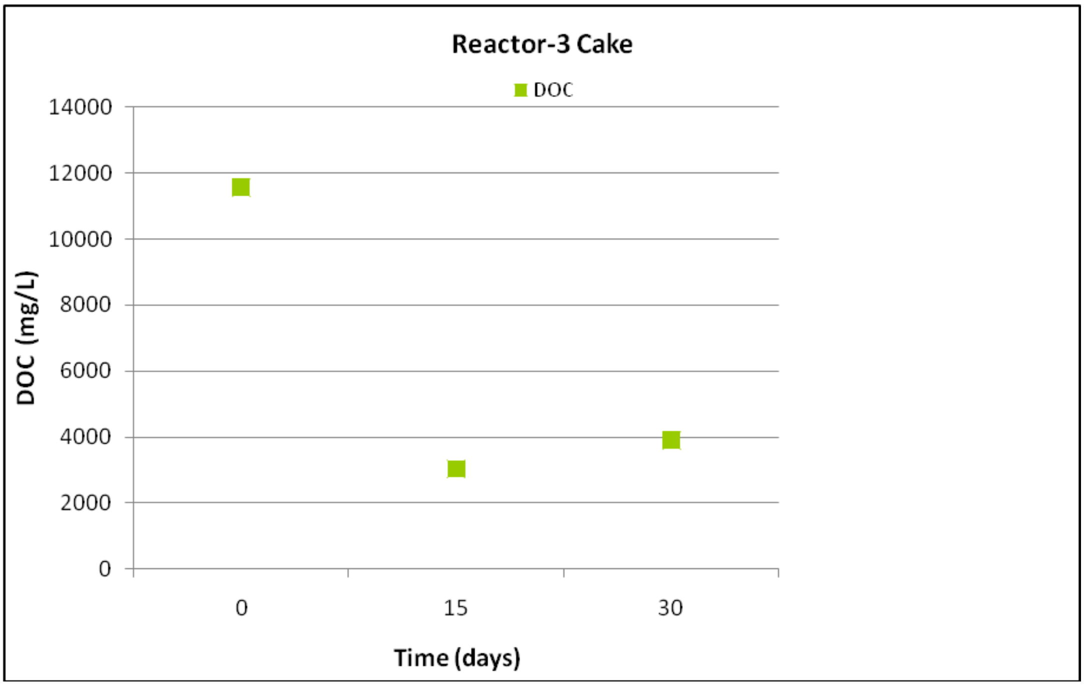

Figure 5.28: Sludge cake analysis DOC results for reactor-3

An average DOC removal rate was monitored as 66% for reactor-3. Final-point (day 30) increase for reactor-3 sludge cake DOC value, is considered to be caused by experimental method. Related method (TS 8195 EN 1484) states margin of error as up to 20%.

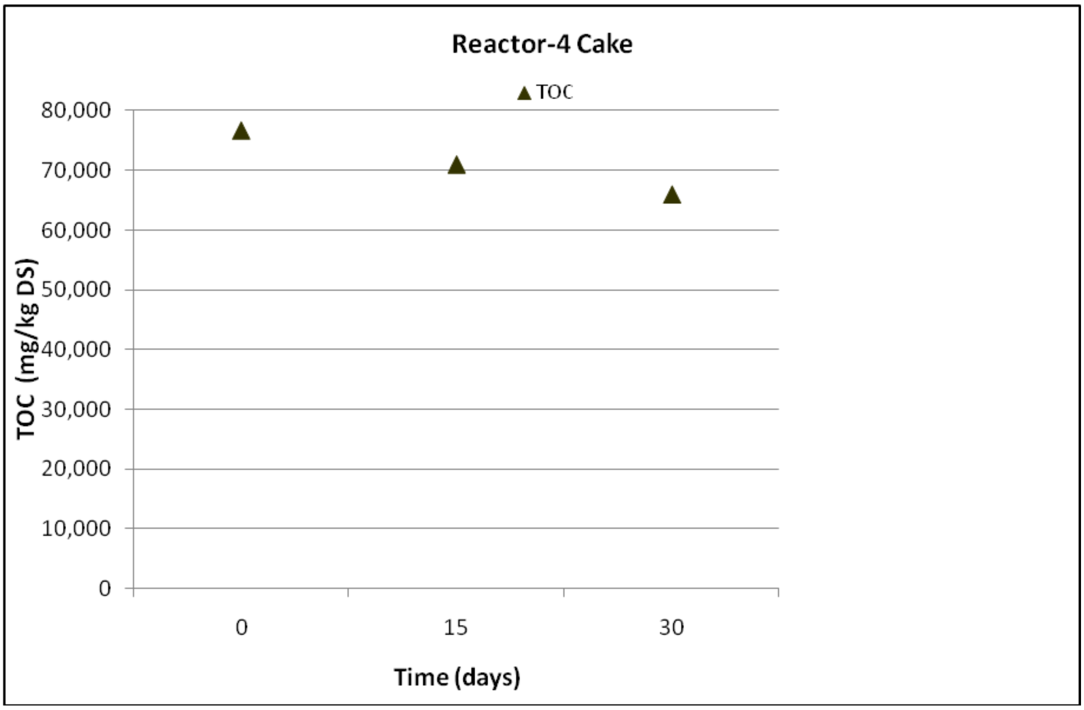

Figure 5.29: Sludge cake analysis TOC results for reactor-4

Very limited TOC reduction, 14%, was observed for reactor 4. Observing aerobic stabilization in-reactors results, it can be seen that a solid ratio between TOC and SS values (TOC/SS: 31% +/- 4%) for reactor-4 was found which shows that, sludge cake TOC levels will not differ noticeably.

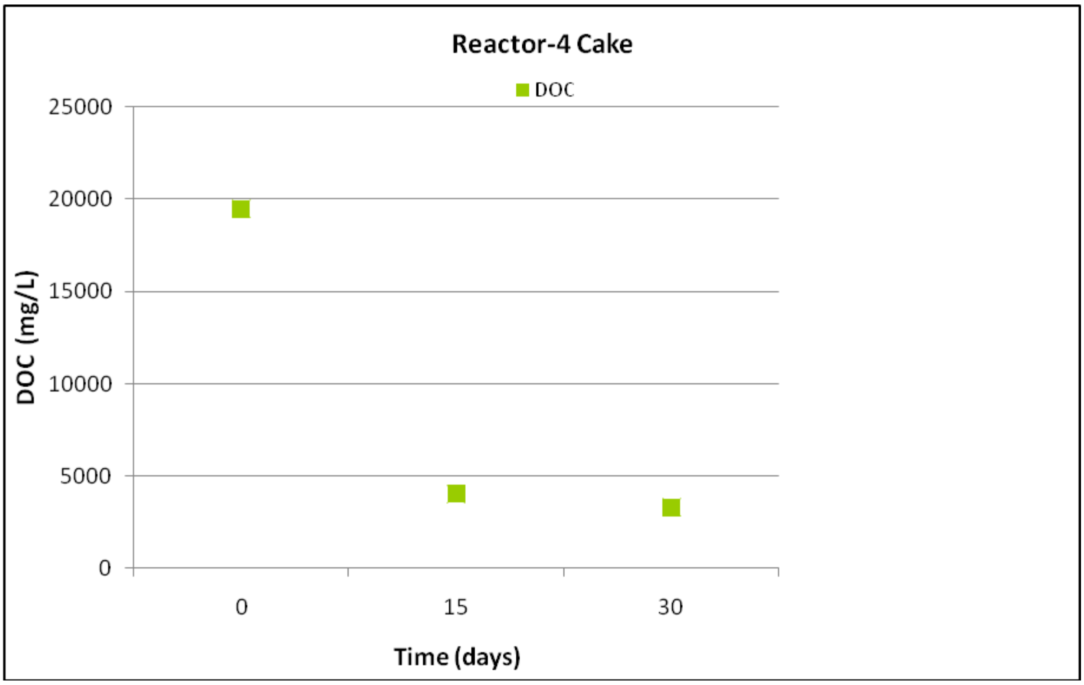

Figure 5.30: Sludge cake analysis DOC results for reactor-4

A high DOC removal rate was monitored as 83% for reactor-4. Unlike reactor-1 and reactor-3, no increase was observed within reactor-4 sludge cake DOC values. Therefore, when compared to reactor-1 and reactor-3, margin of error for this analysis is considered to be smaller and obtained results are regarded as more reliable.

TOC (cake) values varied between 47,000 – 77,000 mg/kg DS considering all four reactors, limited TOC reduction was achieved for reactors 1 and 2 whereas further limited TOC reduction was observed for reactors 3 and 4. DOC (cake) values fluctuated between 3000 – 19,500 mg/L considering all four reactors, even though starting (day 0) DOC values changed significantly between reactors, final (day 30) values were all within a close range.

Aerobic stabilization overview based on sludge cakes removal rates is presented in Table 5.6.

Table 5.6: Aerobic stabilization general overview (sludge cakes)

	TOC (mg/kg DS)	**DOC (mg/L)**
Reactor-1	Limited removal	Limited removal
Reactor-2	Limited removal	Average removal
Reactor-3	Limited removal	Average removal
Reactor-4	Limited removal	High removal

As important criteria parameters for sludge to be disposed at a landfill, sludge cake TOC values, except for reactor-2, are determined to be above the legal limit values. As well, DOC sludge cake values are found to be higher than legal limit values for every reactor at all times. Therefore, aerobically stabilized sludge will be considered hazardous waste based on national legislation limit values for TOC and DOC parameters.

Although, mostly limited removal rates were observed and legal standards were not met, it was monitored that aerobic stabilization did occur in reactors. As for, in-reactor removal rates, up to 35% SS removal and up to 50% VSS removal were achieved. In addition, up to 43% TOC removal and up to 26% DOC removal were also obtained. Evaluation of aerobic sludge stabilization should be based on an overall look, which also includes in-reactors results, not just sludge cake results. Further evaluations and related suggestions are provided in the next chapter.

Another aspect of the study was to investigate if there is an interrelationship between parameters COD and TOC, carrying out analysis on four reactors, each with different influent COD levels from low to high. Study's findings point out that there is no correlation between influent COD value of wastewater and TOC value of sludge cake.

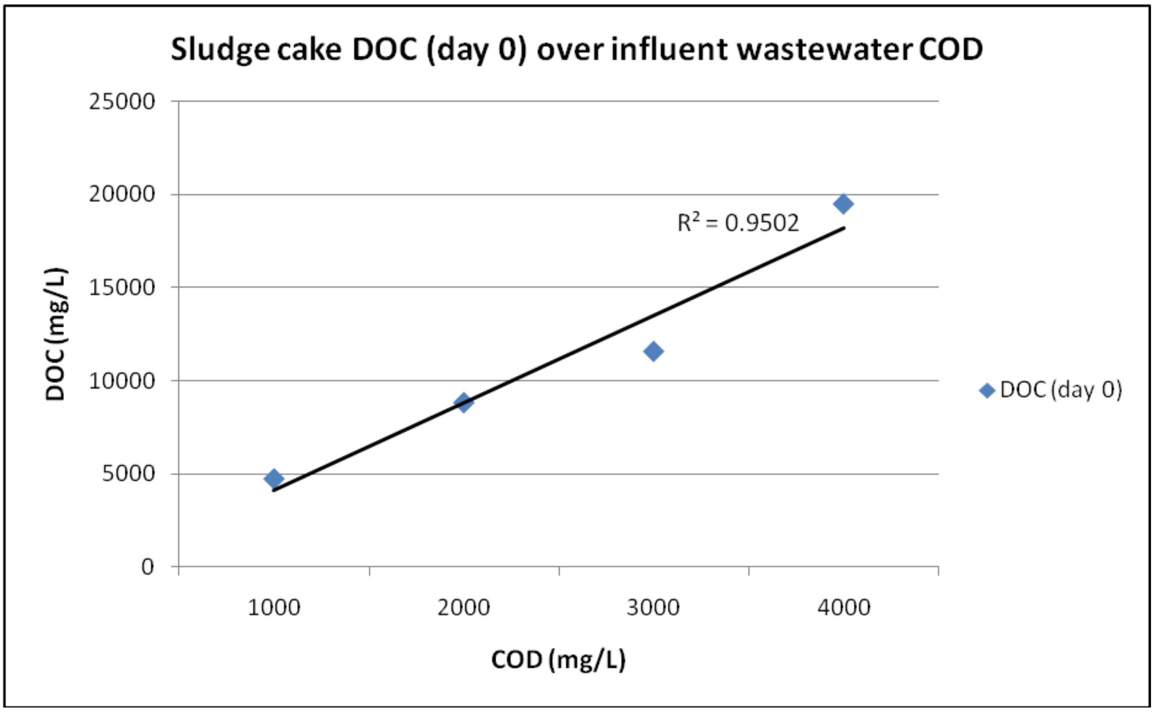

Figure 5.31: Sludge cake DOC initial results over influent wastewater COD levels

On the other hand, a correlation between wastewater COD value and initial (day 0) sludge cake DOC value was found, as can be seen in Figure 5.31. A linear trendline with a correlation coefficient of 0.95 was obtained when sludge cake DOC initial results were charted over influent wastewater COD levels.

This relation can be theoretically based on carbon balance, in wastewater stream certain (yield) fraction of organic matter used for biomass synthesis causes some organic carbon to be trapped in sludge, which later becomes available in sludge cake eluent.

Additionally, variations of pH values for all reactors are shown in Figure 5.32.

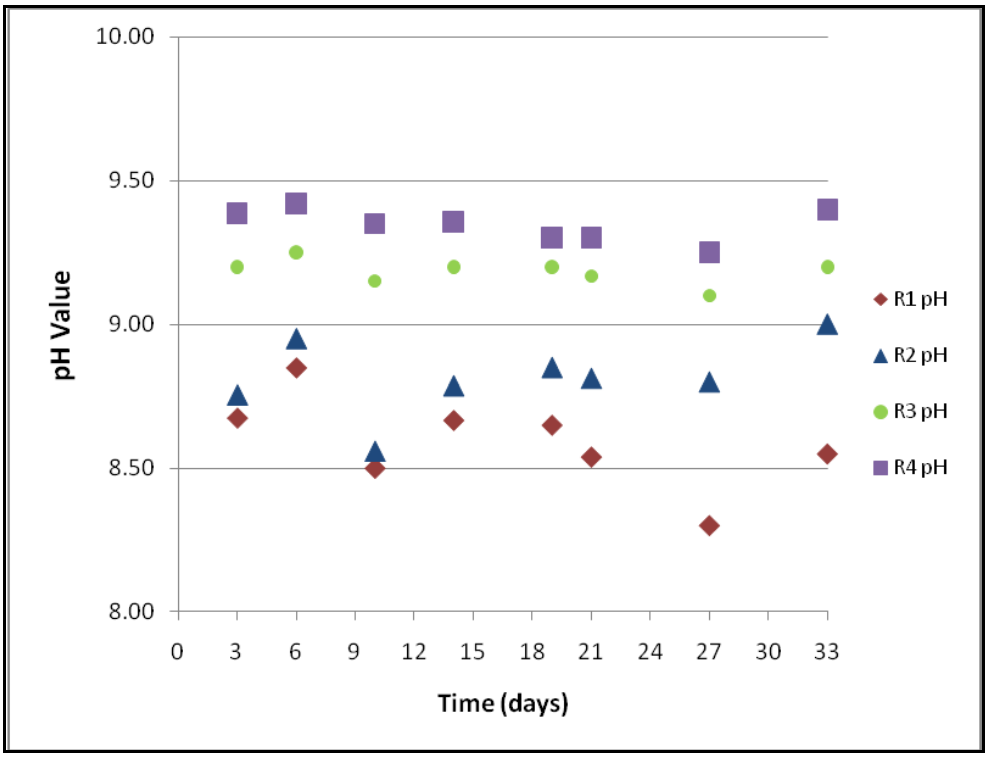

Figure 5.32: Aerobic stabilization pH results

As can be seen pH values in all reactors are restricted within a narrow range of pH 8.5-9.5. As organic strength of wastewater increases, higher pH values were observed within reactors, however high strength wastewater undergoes more balanced reactions in terms of pH, causing less fluctuation.

6. CONCLUSION AND RECOMMENDATIONS

Brewery wastewater treatment sludge in its raw form was considered hazardous waste based on national legislation limit values for TOC and DOC parameters. Studies were carried out on sludge cakes formed in laboratory from brewery wastewater fed reactors with four different influent COD values. These studies indicated that even after aerobic stabilization, TOC and DOC values for sludge cakes were not reduced to the levels under legal limitations. Therefore, in accordance with Regulation on the Control of Hazardous Waste (Date: 14/03/2005 and No: 25755) Annex-11A, sludge cakes are found to be non-suitable for disposal at inert and/or non-hazardous waste landfill sites.

Failure to meet these legal values after aerobic stabilization can be evaluated in different ways, however considering in-reactor parameters such as VSS, TOC and DOC it can be observed that aerobic stabilization takes place and provides some removal for these parameters. In reactor VSS removal rates occurred between 15-50%, whereas average rates for in reactor TOC and DOC parameters monitored to be as 39% and 22% respectively.

Further research should be carried out on stabilization of brewery sludge with and without yeast, including studies on biological treatability and process kinetics. A previous study based on same solids leaching method indicates high DOC levels (≈10,000 mg/L) for yeast, which directly increases sludge cake DOC values. In addition, supplementary research should be conducted on sludge disintegration and its combination with sludge stabilization (aerobic/anaerobic). Moreover, alternative final disposal methods to landfill should be discussed, especially for organically rich brewery wastewater treatment sludge. Final disposal alternatives include incineration (cement kilns), compost and land application. A favorable disposal method can be land application also known as agricultural use, which provides sludge to be reused as a nutrient rich source in form of fertilizer or soil conditioner.

Interrelationship between parameters COD and TOC were also analyzed, conducting analysis on four reactors, each with different influent COD levels from low to high. Results obtained from this study indicate that there is no correlation between influent COD value of wastewater and TOC value of sludge cake. However, a correlation between wastewater COD value and initial sludge cake DOC value was found, as reactors fed with high COD wastewater produced high DOC sludge cakes and vice versa. Unlike sludge cake TOC parameter, both influent wastewater COD and sludge cake DOC parameters are represented in same units as concentration values, therefore these two parameters share the same base to form a correlation upon. Within the same carbon cycle, certain fraction of organic constituents in wastewater end up in sludge, which they later are detected in eluent organic carbon values.

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