ANAEROBIC AND COMBINED ANAEROBIC/AEROBIC DIGESTION OF THERMALLY HYDROLYZED SLUDGE

Charan Tej Tanneru

Thesis submitted to the faculty of the Virginia Polytechnic Institute and
State University in partial fulfillment of the requirements for the degree
Of

Master of Science
In
Environmental Engineering

John T. Novak, Chair
Sudhir N. Murthy
Gregory D. Boardman

November 12, 2009
Blacksburg, VA

Keywords: mesophilic anaerobic digestion, aerobic digestion, solids removal, COD removal
Ammonia removal and biosolids odors

ANAEROBIC AND COMBINED ANAEROBIC/AEROBIC DIGESTION OF THERMALLY HYDROLYZED SLUDGE

Charan Tej Tanneru

ABSTRACT

Sludge digestion has gained importance in recent year because of increasing interest in energy recovery and public concern over the safety of land applied biosolids. Many new alternatives are being researched for reducing excess sludge production and for more energy production. With an increase in solids destruction, the nutrients that are contained in sludge especially nitrogen, are released to solution and can be recycled as part of filtrate or centrate stream.

Nitrogen has gained importance because it has adverse effects on ecosystem's as well as human health. NH_4^+, NO_2^-, NO_3^-, and organic nitrogen are the different forms of nitrogen found in wastewater. While ammonia is toxic to aquatic life, any form of nitrogen can be utilized by *cyanobacteria* and result in eutrophication. NO_2/NO_3, if consumed by infants through water, can affect the oxygen uptake capability. Hence, removal of nitrogen from wastewater stream before discharging is important.

The main purpose of this study was to evaluate the performance of the Cambi process, a thermophylic hydrolysis process used as a pre-treatment step prior to anaerobic digestion. Thermal hydrolysis, as a pre-treatment to anaerobic digestion increases the biological degradation of organic volatile solids and biogas production. The thermal hydrolysis process destroys pathogens and hydrolysis makes the sludge readily available for digestion, while at the same time facilitating a higher degree of separation of solid and liquid phases after digestion.

Experiments were conducted in three phases for anaerobic digestion using the Cambi process as pre-treatment. The phases of study includes comparison of two temperatures for thermal hydrolysis (Cambi 150°C and Cambi 170°C), comparison of two solid retention times in anaerobic digestion (15 Day and 20 Day) and comparison of two mesophilic temperatures in anaerobic digestion (37°C and 42°C).

Different experimental analyses were conducted for each phase, such as pH, bio-gas production, COD removal, VS destruction, nitrogen removal, odor and dewatering characteristics and the results are compared among all the phases.

The second part of the study deals with aerobic digestion of anaerobically digested sludge for effective nitrogen removal and additional VS destruction, COD removal. An aerobic digester is operated downstream to anaerobic digester and is operated with aerobic/anoxic phase for nitrification and de-nitrification. The aerobic/anoxic phases are operated in time cycles which included 40minutes/20minutes, 20minutes/20minutes, full aeration, 10minutes/30minutes, and 12minutes/12minutes. Different time cycles are experimented and aerobic digester is optimized for effective nitrogen removal. 12minutes aerobic and 12 minutes anoxic phase gave better nitrogen removal compared to all the cycles. Over all the aerobic digester gave about 92% ammonia removal, 70% VS destruction and 70% COD removal. The oxygen uptake rates (OUR's) in the aerobic digester are measured corresponding to maximum nitrogen removal. The OUR's are found to be close to 60 mg/L during maximum nitrogen removal. The effluent from both anaerobic digester and aerobic digester was collected and analyzed for dewatering capability, cake solids concentration and odor potential.

ACKNOWLEDGEMENTS

I sincerely acknowledge the valuable guidance and support that I received from my advisor, Dr. John T. Novak throughout this research work and my graduate study. His encouragement and enthusiasm inspired me. I am grateful to him for funding me and keeping me financially stable throughout my study at Virginia Tech. I would also like to thank my committee members, Dr. Sudhir N Murthy and Dr. Gregory Boardman, for their inputs and timely guidance.

I would like to acknowledge Washington D.C Water and Sewer Authority (DCWASA) for providing support and funding for this research. I am grateful to Dr. Sudhir Murthy at DCWASA for his enthusiasm and guidance during the research.

I thank Dr. Charles Bott for his valuable guidance during research.

I gratefully acknowledge Julie Petruska and Jody Smiley for their advice and help in lab. I would also like to thank Betty Wingate and Beth Lucas for their invaluable assistance in administrative issues. My special thanks go to Chris Wilson for his constructive feedback and guidance on this research. I learnt a lot from my fellow researchers and would like to thank Jongmin Kim, Dave Riedel and Sarita Banjade for their discussions and suggestions during this study.

I am grateful for my father who is my first inspirer, my mother for her support and my brother for his guidance. I would like to thank my friend Pavani who supported and helped me throughout my Master's Degree.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 LITERATURE REVIEW

1.1 Introduction

Anaerobic sludge treatment processes are used for stabilizing organic matter coming from primary clarifiers and secondary clarifiers and converting the organics to methane, a fuel which can be used to generate energy (McCarty *et al.,* 1986).

Sludge digestion is a biological process in which organic solids are decomposed into stable substances. Digestion reduces the total mass of solids, destroys pathogens, and makes it easier to dewater or dry the sludge (Grady *et al.,* 1999). Generally there are two optimum temperatures in anaerobic digestion, mesophilic (35^{o} C) and Thermophilic (55^{o} C). Recently, anaerobic digestion in a lower temperature zone has been considered as an energy saving treatment process (Cheol *et al.,* 1997).

As a result of wide application of waste activated sludge process, excess sludge presents serious disposal problem. Thermal hydrolysis pre-treatment for waste activated sludge that has been invented to reduce this problem. The Cambi process is one type of thermal hydrolysis process (Neyens *et al.,* 2003). Anaerobic digestion with thermal hydrolysis as pre-treatment has given good results in terms of VS removal, COD removal and biogas production and is one of pertinent process for activated sludge pretreatment available in the market (Camacho *et al.,* 2008).

However, anaerobic digestion builds up ammonia while degrading organic matter. Lab-scale investigation showed that the stabilization of anaerobically digested sludge increases with post-aerobic digestion (Parravicini *et al.,* 2006). A digester operated with an aerobic phase and an anoxic phase has many advantages over the aerobic digestion alone. Alternating aerobic/anoxic provides alkalinity recovery, energy saving and nitrogen removal (Al-Ghusian *et al.,* 1995).

The main purpose of this project is to evaluate the performance of a thermal hydrolysis process as a pre-treatment step prior to anaerobic digestion. The first phase of study deals with anaerobic digestion with Cambi process as pre-treatment. Three main conditions are investigated,

(a) Comparison of two temperatures in the Cambi process.

(b) Comparison of two solid's retention time in anaerobic digestion.

(c) Comparison of two mesophilic temperatures in anaerobic digestion.

The second phase of study is concerned with nitrogen removal in an aerobic digester that follows anaerobic digestion. An aerobic digester is connected downstream to anaerobic digester and is operated with an alternating aerobic/anoxic phase. The results will be useful for evaluating the advantages and disadvantages of Cambi process, coupled with sequential anaerobic and aerobic digestion.

1.2 Pre-Treatment prior to Anaerobic Digestion

Sludge is the major solid waste from biological treatment processes. Anaerobic digestion is the best available technique to prepare sludge for land application (Bougrier *et al.,* 2006). However, this cannot always be applied on all waste water treatment plants (WWTP) because of limited space. The best solution for this is to minimize the footprint of the sludge treatment process. This can be achieved by performing a pre-treatment prior to anaerobic digestion (Chauzy *et al.,* 2005). This study investigated thermal hydrolysis as a pretreatment step. Results showed that thermal pre-treatment is suitable for stabilization of sludge, improving dewaterability of the sludge, reducing the pathogens and increasing the bio-gas production (Hariklia *et al.,* 2003). Thermal pre-treatment at high temperatures (100^{o}C-200^{o}C) improved the stabilization of sludge. Thermal pre-treatment in the temperature range from 100^{o}C-180^{o}C destroys cell walls and makes the proteins accessible for biological degradation (Muller 2001). It has been shown that the anaerobic digestion can consistently achieve 55 to 60% volatile solids destruction after thermal hydrolysis (Jolis 2008). In general adding a thermal hydrolysis process as a pre-treatment to anaerobic digestion increases dewatered cake solids by 10-12% over conventional digestion (Camacho *et al.,* 2008). The Cambi process is one such thermal hydrolysis process which was first used in Hamar, Norway in 1995 (Kepp *et al.,* 2000).

Description of Cambi Process

The Cambi process is a thermal hydrolysis process (THP) that is used as a pretreatment for anaerobic sludge digestion to break down cells and release soluble COD mainly in the form of volatile fatty acids, (VFAs) in order to increase the digestibility of the sludge.

Thermal hydrolysis process is a process in which the sludge is heated to high temperatures and subjected to high vapor pressures. (Pickworth *et al.,* 2006, Kepp *et al.,* 2000).

Raw sludge from the wastewater treatment process is dewatered prior to the Cambi thermal hydrolysis in the Cambi process to reduce the volume of the sludge to be treated. Generally belt filter presses are used for dewatering. The dewatered sludge is routed to the hydrolysis pressure vessels (Cambi reactors) for hydrolysis. The reactors operate on a batch basis and are pressurized by 12 bar steam. The operating temperature and pressure vary between 130°C to 180°C and 5 to 8 bar respectively for 20 min to 30 min. Cambi uses a live steam to add heat to the sludge cake. This process produces a sludge that is partially solubilized and the biological cells are disintegrated. The sludge organic matter is then more readily available for digestion. While at the same time the process facilitates a higher degree of separation of solid and liquid phase after digestion. The retention time and pressure can be adjusted and programmed according to the requirements. After one batch is completed the pressure inside the Cambi reactor is released, by means of a pressure release valve, until the pressure reaches 2 bar. This Cambi treated sludge is then pumped to the heat exchangers before it is sent to the anaerobic digesters for sludge digestion. The sludge entering the anaerobic digesters has a reduced temperature of 38°C to 41°C (Pickworth *et al.,* 2006). Fig. 1-1 shows the schematic of sludge digestion by a Cambi unit. The hydrolyzed sludge is cooled and fed to the digesters. This process has the following advantages over a conventional anaerobic digestion process:

- complete sterilization of all pathogens
- increase in biogas production and sludge destruction

- production of class “A” biosolids (Pickworth *et al.,* 2006)

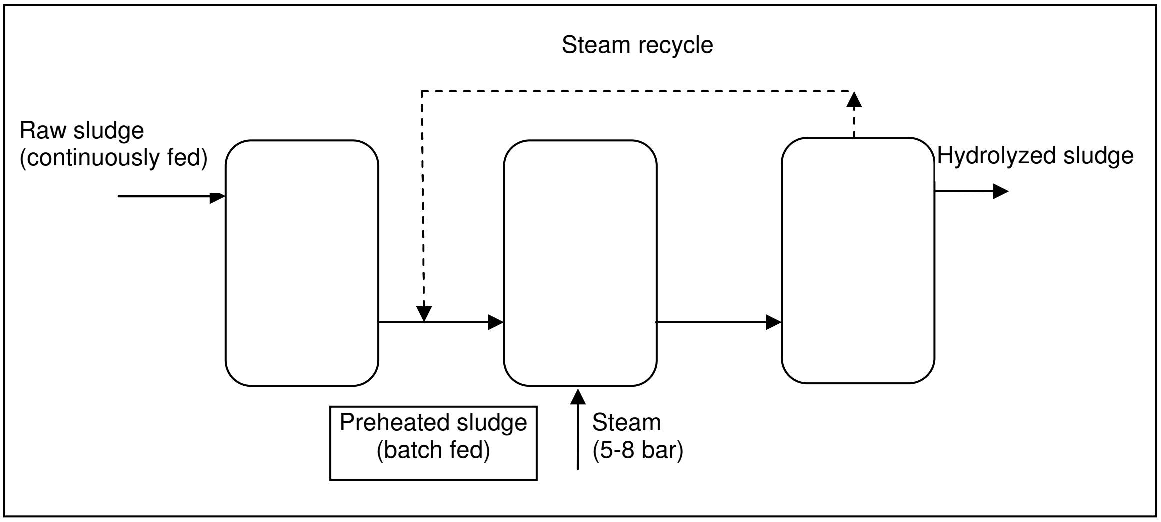


Figure 1-1: Schematic showing Cambi Process

1.3 Anaerobic Digestion

Anaerobic digestion is a biological process that uses bacteria and archaea that function in an oxygen-free environment to convert volatile solids into carbon dioxide, methane, and ammonia. Sludge is treated at a specific solids retention time and at a specific temperature (U.S. EPA, 2003). Anaerobic digestion is a multistep process which includes hydrolysis, acidogenisis, acetogenisis and methanogenisis (Grady *et al.,* 1999).

The first reaction in the series is hydrolysis. Complex organics such as carbohydrates, proteins, and lipids are hydrolyzed by enzymes to sugars, amino acids and long chain fatty acids respectively (Fuentes *et al.,* 2008).

In this second step, the products that are formed in the hydrolysis step are further broken down to volatile fatty acids (VFA) by acidogenic (i.e. fermentative) bacteria. Ammonia (NH_3), Carbon-di-oxide (CO_2) and Hydrogen di sulfide (H_2S) are other byproducts generated this acidogenisis reaction (Appels *et al.,* 2008).

The organic acids and alcohols that are formed during acidogenisis are digested by acetogens to form acetic acid and as well as CO_2 and Hydrogen (H_2) (Appels *et al.,* 2008). This is called acetogenisis. The production of hydrogen is very critical because it serves as primary substrate for the production of methane (Grady *et al.,* 1999).

This is the final stage, methanogenisis results in the formation of methane (CH_4). Two types of methanogenic archaea are involved in this process. Aceticlastic methanogens split acetic acid in to methane and carbon dioxide. Hydrogen oxidizing archaea use hydrogen as an electron donor and carbon dioxide as an electron acceptor to produce methane (Grady *et al.,* 1999, Appels *et al.,* 2008).

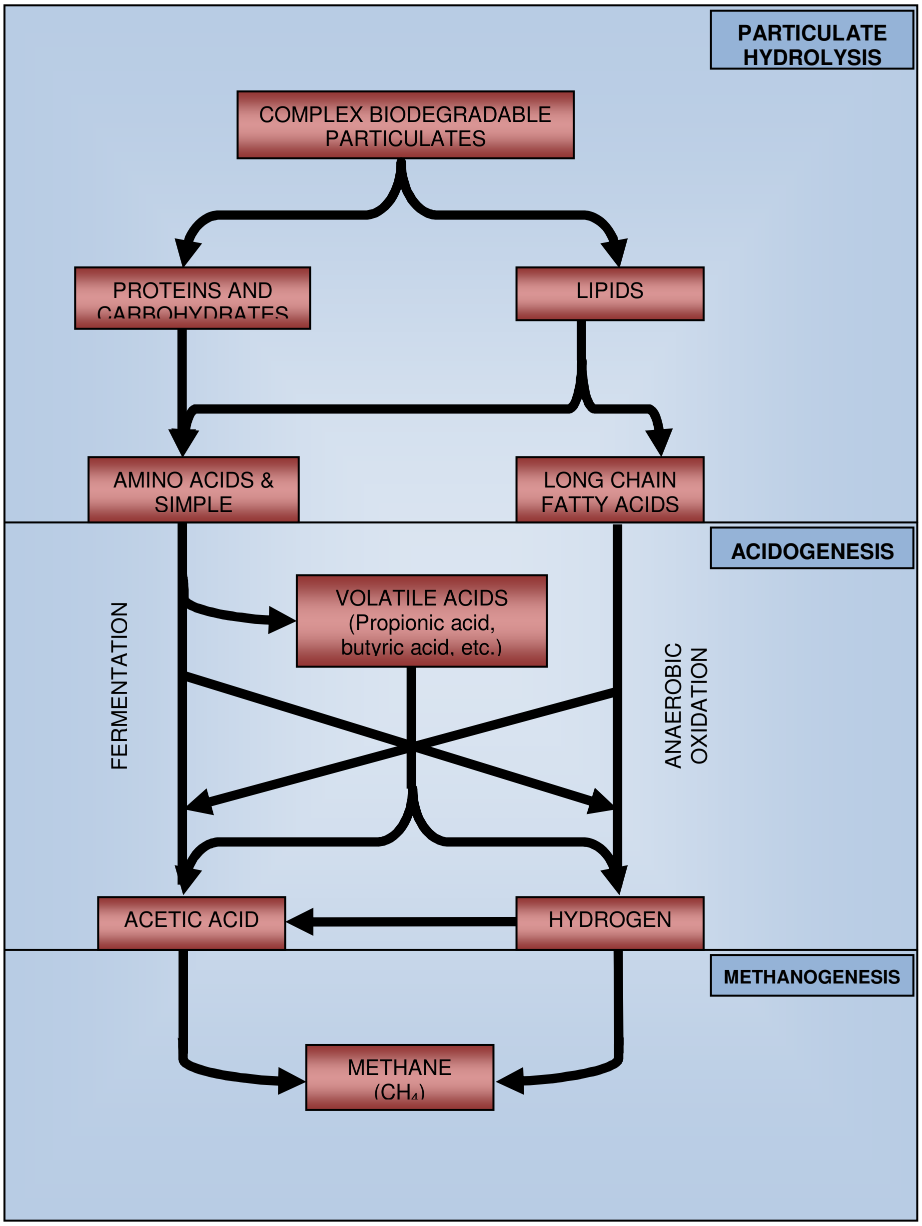


Figure 1-2: Multistep Nature of Anaerobic Operations

Anaerobic digestion is one of the most widely used sludge stabilization processes in the world. The digestion process should be operated at steady state for the better performance of the process. Various factors govern the performance of the digester. These are pH, temperature, solids retention time (SRT), alkalinity, bio-gas production ,accumulation of volatile fatty acids (VFA), organic loading rate, total hydraulic loading and level of xenobiotic compounds (Leitao *et al.,* 2006, Cohen *et al.,* 1982, Zhang *et al.,* 1994, Moen *et al.,* 2003, Grady *et al.,* 1999).

The optimum pH of the anaerobic digestion is 6.8-7.4 (Grady *et al.,* 1999). The methanogenic activity will slow considerably with pH less than 6.3 and higher than 7.8 and this will inhibit the biogas production (Leitao *et al.,* 2006). Lower pH will result in the growth of filamentous bacteria and a high pH results in buildup of ammonia (Grady *et al.,* 1999).

Accumulation of VFA's result during overloading and sudden variations in organic loading rates (Leitao *et al.,* 2006). Volatile fatty acids are weak acids that are dissociated by neutral pH (Grady *et al.,* 1999). Presence of high VFA's are detrimental to methanogenic activity through toxic action of un-ionized VFA's and they always suggest a reactor imbalance. It is always beneficial to maintain favorable pH and moderate VFA concentration so that no drastic effects are imposed on the system (Cohen *et al.,* 1982).

Major nuisance organisms in anaerobic operations are sulfate reducing bacteria, and they are present in large numbers when the waste water contains significant amount of sulfate. The main problem with these organisms is that they compete with acetate and H_2 for the electron donor and this results in production of sulfide and reduces the amount of methane formed (Grady *et al.,* 1999).

Solids retention time plays very important role in the design of the anaerobic process. It represents the average length of time a particulate constituent stays in the reactor. It is the most important design parameter available for an engineer as it is directly related to specific growth rate of biomass in a continuosly stirred tank reactor (Grady *et al.,* 1999). Retention time has considerable effect on the population levels of methanogens, homoacetogens as well as sulfate reducing bacteria and the composition of fermentative products (Zhang *et al.,* 1994).

Other factors that affect anaerobic processes include high concentrations of xenobiotic compounds, heavy metals, detergents and oxygen. These will generally result in accumulation of VFA's and reduction of pH (Leitao *et al.,* 2005).

Temperature plays very important role in anaerobic digestion. There are two critical temperature ranges mesophilic digestion (35-40^{o}C) and thermophylic digestion (50-60^{o} C). Recently, anaerobic digestion in lower temperature zone has been suggested as an energy saving treatment processes (Cheol *et al.,* 1997).

1.4 Anaerobic digestion with Cambi process as pre-treatment

Thermal hydrolysis is a pre-treatment process for anaerobic digestion. Research from the past several years showed that thermal hydrolysis prior to anaerobic digestion results in net energy production from the system because of increased biodegradability and reduced digester heating requirements (Camacho *et al.,* 2008).

Thermal hydrolysis is a process in which sludge is heated to 130-180^{o}C for about 30 minutes at a vapor pressure. Cambi process was studied beginning in 1990 and the first full scale plant was started in 1995 at HIAS Norway. Currently there are around 20 plants around the world that are successfully operating with Cambi process (Pickworth *et al.,* 2006).

The main advantages of the Cambi process lies in increasing dewaterability, higher biogas production and reduced the digester volume. Prior to hydrolysis, sludge is dewatered and this results in high solids anaerobic digestion at about 10-12% (feed concentration). The degree of stabilization shows that 60% of COD is converted to biogas and the stabilized sludge free of pathogens (Kepp *et al.,* 2000).

Initial results of this high solid anaerobic digestion process gave 60-70% of the volatile solids reduction, which is 10-20% higher than conventional digestion. Results showed 50% reduction of digester volume and 50% mass reduction due to better dewaterability (Pickworth *et al.,* 2006, Jolis 2008, Kepp *et al.,* 2000).

Fjaergard (2001) did a pilot study in San Francisco during 2001-2003 on pre-treatment processes at high temperature for both mesophilic and thermophilic digestion. After nearly one year he showed that, disturbances like pH, temperature and feeding rate that can strongly influence thermophilic digestion but have little or no impact on mesophilic digestion.

1.5 Aerobic Digestion

In aerobic digestion sewage sludge is bio-chemically oxidized by bacteria. Generally the aerobic micro-organisms are supplied with oxygen by vigorous mixing or forcibly injecting air or oxygen (U.S. EPA, 2003). The solids are oxidized with oxygen or nitrate-N as the terminal electron acceptor (Grady *et al.,* 1999). Aerobic digestion produces sludge i.e. suitable for disposal from small scale WWTP's because it produces more stabilized sludge, free from nuisance odors and is of low cost (Matsuda *et al.,* 1988).

Process Description

Aerobic digestion hydrolyzes biodegradable particulate organic matter and converts it into ammonia, phosphate and biodegradable soluble organic matter. The bio-degradable soluble organic matter is then converted in to CO_2 and H_2O and active biomass by heterotrophic bacteria. This active biomass undergoes decay forming CO_2 and H_2O and inactive biomass, which is non-biodegradable particulate organic matter or debris (Grady *et al.,* 1999).

As the aerobic digestion process releases nutrients, the nitrogen cycle plays very important role. In domestic waste waters, most of the nitrogen is in the form of ammonia (NH_3) and organic nitrogen. Converting organic nitrogen to NH_3 is called ammonification and if the waste water contains excess ammonia nitrification occurs which converts NH_3 to nitrate. In some aerobic digesters, both aerobic and anoxic operation will lead to denitrification in which nitrate is converted to nitrogen gas (N_2) with nitrite as an intermediate (Grady *et al.,* 1999).

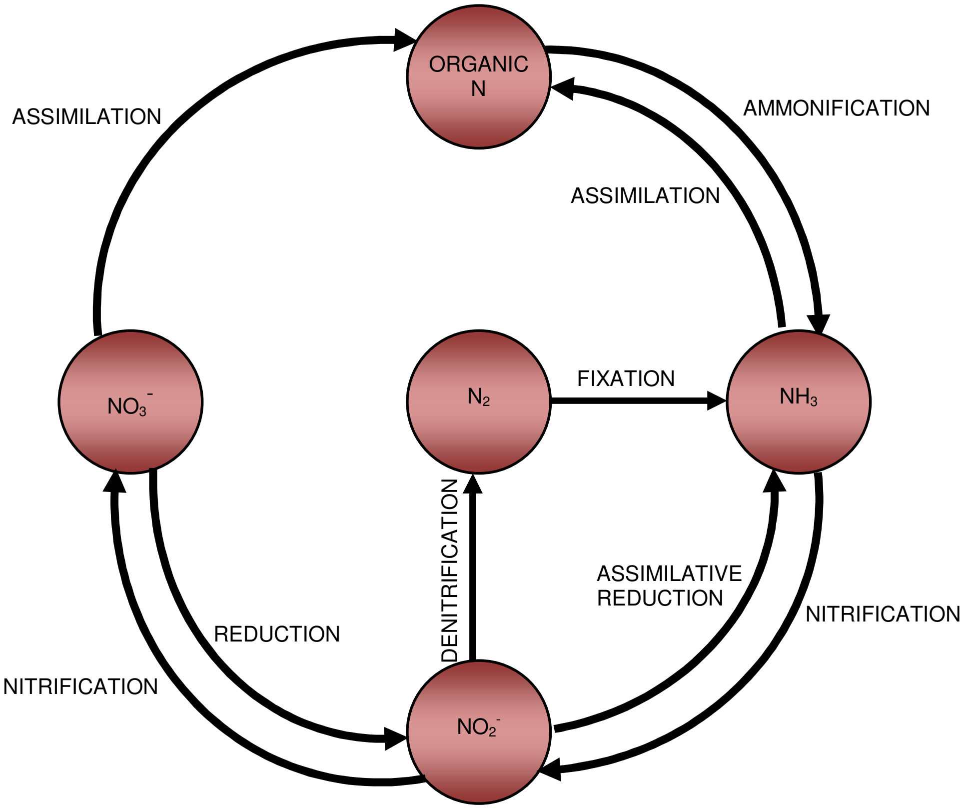


Figure 1-3: Nitrogen Cycle

Factors affecting the performance of Aerobic Digestion

Aerobic digestion is affected by various factors which includes pH, temperature, solids retention time, concentration of sludge, mixing, oxygen uptake rate (OUR) and type of operation (full aeration or aerobic/anoxic) (Ganczarczyk *et al.,* 1980, Matsuda *et al.,* 1988, Khalili *et al.,* 2000, Warner *et al.,* 1986, Huang *et al.,* 1985, Grady *et al.,* 1999).

SRT exerts a very dominant effect in the performance of the biochemical operations. If the SRT is maintained too low biodegradable organic matter will be wasted and washed out from the reactor. The corresponding figure shows the SRT's required for different aerobic/anoxic systems (Grady *et al.,* 1999).

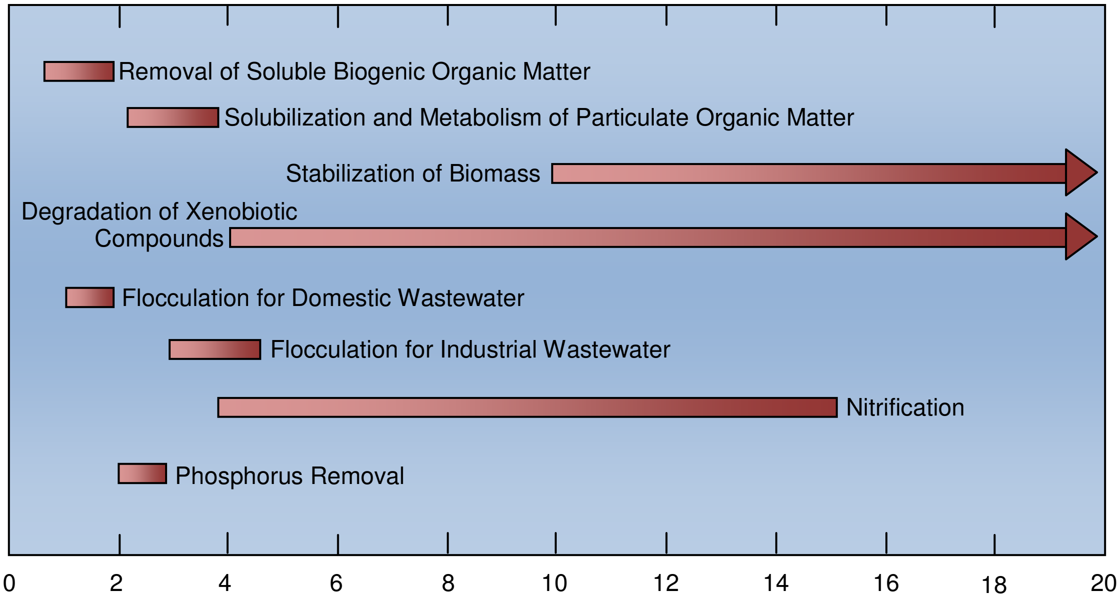


Figure 1-4: Typical SRT ranges for various biochemical conversions in aerobic/anoxic bioreactor systems at 20°C.

pH plays an important role in aerobic digestion; it is linked to nitrogen cycle. Variations in pH directly affect the nitrification and denitrification. The minimum pH was 6 and the maximum was found to be 8 for best aerobic and anoxic operation (Al-Ghusian *et al.,* 1995).

Tyagi *et al.,* (1990) studied mesophilic and thermophylic aerobic digestion for municipal sludge and showed that nitrification is inhibited at higher temperature range exceeding 40^{o}C.

Combined aerobic and anoxic degradation has been gaining lot of attention in recent years. This system is successfully tested by various researchers. Aerobic digestion of waste activated sludge with aerobic and anoxic operation is as efficient as full aeration in terms of volatile solids reduction. Denitrification helps maintain the alkalinity and hence the pH to remain stable (Warner *et al.,* 1986).

Oxygen Uptake Rates in Aerobic Digestion

As the activated sludge process involves various biochemical reactions, the microbial activity (substrate utilization) and viability (active microbial mass concentration) plays very important role in design of the process. Research has shown that the oxygen uptake rate (OUR) is a promising parameter that can be used to assess the microbial activity and viability (Huang *et al.,* 1985). The degree of stabilization in the aerobic digester is generally measured using the specific oxygen uptake rate (Grady *et al.,* 1999).

Operating an Aerobic digester with Aerobic/Anoxic stages

Nitrogen removal has long been established shown to occur by nitrification followed by denitrification. However the greater challenge is to identify the conditions for the two phenomena can coexist, because of their contrasting requirements. Nitrification is a two step process: oxidation of ammonia from NH_4^+ to NO_2^- by the ammonia-oxidizing bacteria (AOB) and then oxidation of nitrite from NO_2^- to NO_3^- by the nitrite-oxidizing bacteria (NOB) (Tchobanoglous *et al.,* 2003, Li *et al.,* 2008).

Nitrifying bacteria are chemoautotroph- e.g., *Nitrosomonas and Nitrobacter.* Denitrification in turn is a process that reduces nitrate to N gas. It is primarily carried by heterotrophs (facultative bacteria) such as *Paracoccus denitrificans.* The AOB and NOB require oxygen to carry out the nitrification steps while the denitrifying bacteria are inhibited by the presence of oxygen. The challenge is to create a balance or a cycle where the aerobic and anoxic conditions occur without interfering with each other. This can potentially be achieved by controlling the oxygen supply in a timely manner, i.e. by maintaining alternating aerobic phase and anoxic phase. Oxygen is supplied during the aerobic phase and turned off for the anoxic phase (Grady *et al.,* 1999).

Enhanced nitrogen removal has gained lot of importance in recent years because of increasing restriction on nitrogen discharges. The process involves three microbial steps so it is important to see that all the three steps are carried out without interruption. While the step of denitrification is generally stable, nitrification is highly unstable due to the sensitive nature of the nitrifying bacteria and their growth kinetics. The nitrifying bacteria have a slower growth rate compared to the denitrifying bacteria and are easily effected by the presence of unfavorable compounds. Low growth rates and inhibition by toxic compounds present in the influent can have a long term effect on the nitrification process (Winther *et al.,* 1996, Sinkjær *et al.,* 1996). While the slower growth rate is due to inherent metabolic reasons, the inhibition of the step is often due to toxic compounds. The type of wastewater being treated, pH, substrate concentration, temperature, oxygen concentration and the presence of other compounds determine the extent of inhibition. Industrial discharges can also be a source of inhibition (Bing He *et al.,* 2007).

Nitrogen can be effectively removed by adopting air on (aerobic phase) and air off (anoxic) sequences in the aerobic digester i.e. during the aerobic phase nitrification takes place and during anoxic phase denitrification takes place. Nitrification/denitrification is achieved by cycling between aerobic/anoxic conditions. The time interval for each phase is critical. The figure shows carious cycle times that have been used for maximum nitrogen removal (Batchelor, 1983).

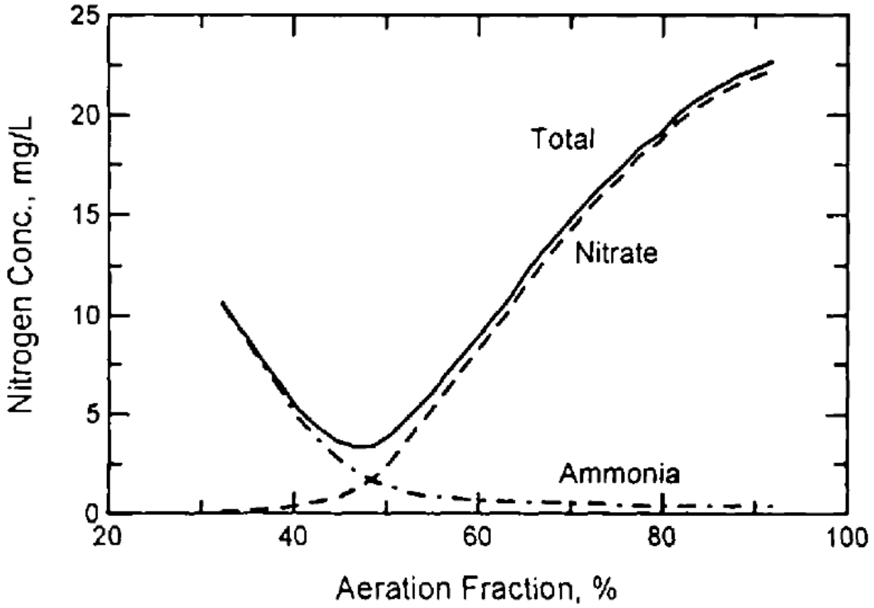


Figure 1-5: Effect of aeration fraction on effluent concentrations of ammonia and nitrogen.
Reproduced from Batchelor, 1983.

1.6 Post-Aerobic Digestion of Anaerobically treated Sludge

The degree of stabilization of anaerobically digested sludge can be enhanced by introducing post-aerobic digester downstream of the anaerobic digester (Parravicini *et al.,* 2006). Post aeration treatment has several advantages; the organic solids can be reduced further by up to 20%, the corresponding COD removal and enhanced nitrogen removal by intermittent aeration through nitrification and denitrification (Parravicini *et al.,* 2008). Akunna *et al.,* 1994 showed that the amount of ammonia nitrogen to be nitrified depends on the amount of organic matter in the digested effluent. He was able to achieve 70% ammonia removal and 60% COD removal for anaerobic digestion and post aeration treatment.

Kumar (2006) studied combined anaerobic and post aerobic digestion with different SRT's. He found better ammonia removal as the SRT is increased; he got an overall 80% ammonia removal. Banjade (2008) studied sequential anaerobic and aerobic digestion and achieved around 62% VS reduction, 70% COD reduction.

1.7 Biosolids Odors and Dewatering Characteristics

Biosolids may be malodorous as well as be of concern with regard to public health (De Michele *et al.,* 2000). Odorous emissions from sewage systems and WWTP's can cause serious problems in the vicinity of the plant. Odorants present in the liquid phase are emitted into the ambient air at the liquid-gaseous interface (Frechen *et al.,* 1998).

Generally anaerobic digestion is used to process sludge for land application, but research has shown that anaerobic digestion and dewatered biosolids cakes can generates unacceptable odors (Murthy *et al.,* 2002). The main odor causing chemicals were found to be volatile inorganic sulfur compounds and volatile organic sulfur compounds (VOSC) which include carbon disulfide, hydrogen-sulfide (H_2S), methanethiol (MT), and dimethyl sulfide (DMS), dimethyl disulfide (DMDS) and trimethyl amine. A better understanding is required concerning the generation of these odors, i.e., whether they are generated immediately after dewatering or slowly over a number of days following dewatering. Methanogens play a key role in the degradation of VOSC's (Novak *et al.,* 2006, Higgins *et al.,* 2006, Kim *et al.,* 2002).

The important mechanisms in the formation of VOSC's are found to be biodegradation of sulfur containing amino acids, cysteine and methionine to form H_2S and MT, methylation of H_2S and MT to form MT and DMS and oxidation of MT to form DMDS (Higgins *et al.,* 2006). Lomans *et al.,* 1999 studied the degradation of DMS and MT in slurries prepared from fresh water sediments. The results suggested that methanogenisis is the major mechanism for the degradation of these compounds. Based on inhibition studies, he concluded that the addition of bromoethane sulfonic acid (BESA) which is considered as methanogenisis inhibitor lowered the degradation of DMS and MT, allowing them to persist at higher levels.

Apart from methanogenisis, sulfate reducing bacteria also degrade DMS and MT depending on the availability of sulfate or sulfide (Lomans *et al.,* 2001). At very low concentrations (µM level), sulfate reducing bacteria compete with methanogens for degradation of DMS and MT in sulfate abundant anoxic sediments (Kiene *et al.,* 1986).

Van Leerdam *et al.,* (2006) studied the degradation and toxicity of VOSC's in sludge. They found that all samples degraded MT, DMS, and DMDS anaerobically. In the presence of sulfate and BESA, degradation of these compounds was coupled to sulfate reduction.

Novak *et al.,* (2006) studied anaerobically digested sludge and dewatered sludge cake, and found that primary VOSC's MT, DMS, DMDS followed a predictable pattern of production, peaking between day 1 and day 7, and then the declining started. DMDS peaked early and the magnitude was very low. After the conversion of MT and DMS to H_2S, the sulfide in the anaerobic sludge cake precipitated as FeS (Higgins *et al.,* 2006).

Novak *et al.,* (2007) studied the role of iron in the odor formation. They found that volatile solids reduction generally increased as the iron content of the sludge increased and the odors increased with increased iron. Kumar (2006) studied sequential anaerobic digestion and found that an increase in anaerobic digestion SRT decreased odor generation.

References

Akunna, Joseph., Bizeau, Claude., Moletta, René., Bernet, Nicolas., and Héduit, Alain. Combined Organic Carbon and Complete Nitrogen Removal Using Anaerobic and Aerobic Upflow Filters. *Wat. Sci. Tech. Vol. 30, No. 12, pp. 297-306, 1994.*

Al-Ghusain, Ibrahim., and Hao, Oliver J. Use of pH as Control Parameter for Aerobic/Anoxic Sludge Digestion. *Journal of Environmental Engineering, Vol. 121, No. 3, 1995.*

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

Banjade, Sarita. Anaerobic/Aerobic Digestion for Enhanced Solids and Nitrogen Removal. *Master's Thesis, Virginia Polytechnic Institute and State University, 2008.*

Batchelor, B. Simulation of single-sludge nitrogen removal. *Journal of Environmental Engineering 109, 1-16, 1983.*

Bougrier, C., Delgenès, J.-P., and Carrère, H. Combination of Thermal Treatments and Anaerobic Digestion to Reduce Sewage Sludge Quantity and Improve Biogas Yield. *Process Safety and Environmental Protection, 84(B4): 280-284, 2006.*

Camacho, P., Ewert, W., Kopp, J., Panter, K., Perez-Elvira, S. I., Piat, E. Combined experiences of thermal hydrolysis and anaerobic digestion – latest thinking on thermal hydrolysis of secondary sludge only for optimum dewatering and digestion. *Water Environment Federation, WEFTEC 2008.*

Chauzy, J., Graja, S., Gerardin, F., Crétenot, D., Patria, L., and Fernandes, P.. Minimization of excess sludge production in a WWTP by coupling thermal hydrolysis and rapid anaerobic digestion. *Water Science & Technology Vol. 52, No.10-11, pp. 255-263, 2005.*

Cheol Cha, Gi., and Noike, Tatsuya. Effect of Rapid Temperature Change and HRT on Anaerobic Acidogenesis. *Wat. Sci. Tech. Vol. 36, No. 6-7, pp. 247-253, 1997.*

Cohen, A., Breure, A. M., van Andel, J. G., and A. van Deursen. Influence of Phase Separation on the Anaerobic Digestion of Glucose-II. *Water Res. Vol. 16, pp. 449-455, 1982.*

De Michele, E. In The National Biosolids Partnership: Background, Progress and the Future. *Proceedings of Biosolids Management in the 21st Century, College Park, Maryland, 2000.*

Fjaergard, T., Sorensen, G., Solheim, O. E., and Seyffarth, T. Cambi Thermal Hydrolysis Combined with Thermophilic/mesophilic Digestion- From Pilot to Full Scale Application at Hamar WWTP. *Proceedings from 11th European Biosolids and Organic Resources Conference, Wakefield, UK, 2006.*

Frechen, Franz-Bernd., and Köster, Wulf. Odor Emission Capacity of Wastewaters-Standardization of Measurement Method and Application. *Wat. Sci. Tech. Vol. 38, No. 3, pp. 61-69, 1998.*

Fuentes, M., Scenna, Nicolás J., Aguirre, Pío A., and Mussati, Miguel C. Application of anaerobic digestion models to biofilm systems. *Biochemical Engineering Journal 38 (2008) 259-269.*

Ganczarczyk, J., Hamoda, M. F., and Wong, Hong-Lit. Performance of Aerobic Digestion at Different Sludge Solid Levels and Operation Patterns. *Water Research, Vol. 14, pp. 627 to 633, 1980.*

Grady, C.P. Leslie, Daigger, Glen T., Lim, H.C., Biological Wastewater Treatment, *Marcel Dekker, New York, 1999.*

Hariklia N. Gavala, Umur Yenal, Ioannis V. Skiadas, Peter Westermann, and Birgitte K. Ahring. Mesophilic and thermophilic anaerobic digestion of primary and secondary sludge-effect of pre-treatment at elevated temperature. *Water Research 37, 4561-4572, 2003.*

He, Sheng-Bing., Xue, Gang., Kong, Hai-Nan., Li, Xin. Improving the performance of sequencing batch reactor (SBR) by the addition of zeolite powder. *Journal of Hazardous Materials 142, 493-499, 2007.*

He, Sheng-Bing., Xue, Gang., Kong, Hai-Nan. The performance of BAF using natural zeolite as filter media under conditions of low temperature and ammonium shock load. *Journal of Hazardous Materials 143, 291-295, 2007.*

Higgins, Matthew J., Chen, Yen-Chih., Yarosz, Douglas P., Murthy, Sudhir N., Maas, Nick A., Glindermann, Dietmar., and Novak, John T. Cycling of Volatile Organic Sulfur Compounds in Anaerobically Digested Biosolids and its Implications for Odors. *Water Environment Research, Volume 78, Number 3, 243-252, 2006.*

Huang, Jerry Y. C., Cheng, Meng-Dawn., and Mueller, James T. Oxygen Uptake Rates for Determining Microbiological Activity and Application. *Water Res., Vol. 19, No 3, pp. 373-381, 1985.*

Jolis, Domènec. High-Solids Anaerobic Digestion of Municipal Sludge Pretreated by Thermal Hydrolysis. *Water Environment Research, Volume 80, Number 7, pp. 654-662, 2008.*

Kepp, U., Machenbach, I., Weisz, N., and Solheim, O. E. Enhanced stabilization of sewage through thermal hydrolysis-three years of experience with full scale plant. *Water Science and Technology, Vol. 42, No. 9, pp. 89-96, 2000.*

Khalili, Nasrin R., Chaib, Embarka., Parulekar Satish J., and Nykiel , David. Performance enhancement of batch aerobic digesters via addition of digested sludge. *Journal of Hazardous Materials, B76, 91-102, 2000.*

Kiene, R. P., Oremland, R. S., Catena, A., Miller, L. G., Capone, D. G. Metabolism of reduced methylated sulfur-compounds in anaerobic sediments and by a pure culture of an estuarine methanogen. *Appl Environ Microbiol 52: 1037-1045, 1986.*

Kim, H., Murthy, S., McConnell, L. L., Peot, C., Ramirez, M., and Strawn, M. Characterization of wastewater and solids odors using solid phase microextraction at a large wastewater treatment plant. *Water Science and Technology Vol. 46, No. 10, pp. 9-16, 2002.*

Kumar, N. Sequential Anaerobic-Aerobic Digestion: A new process technology for biosolids product quality improvement. *Master's Thesis, Virginia Polytechnic and State University, 2006.*

Leitao, Renato Carrhá; van Haandel, Adrianus Cornelius; Zeeman, Grietje; and Lettinga, Gatze. The effects of operational and environmental variations on anaerobic wastewater treatment systems: A review. *Bioresource Technology 97, 1105-1118. 2006.*

Li, H., Liang, X., Yingxu, Chen., Yanfeng, Lian., Guangming, Tian., and Wuzhong, Ni. Effect of nitrification inhibitor DMPP on nitrogen leaching, nitrifying organisms, and enzyme activities in a rice-oilseed rape cropping system. *Journal of Environmental Sciences 20(2): 149-155, 2008.*

Lomans, Bart P., Luderer, Rianne., Steenbakkers, Peter., Poi, Arjan., Van der Drift, Chris., Vogels, Godfried D., and Op den Camp, Huum J. M. Microbial Populations Involved in Cycling of Dimethyl Sulfide and Methanethiol in Freshwater Sediments. *Applied and Environmental Microbiology, Vol. 67, No. 3, P. 1044-1051, 2001.*

Lomans, Bart P., Op den Camp, Huum J. M., Poi, Arjan., Van der Drift, Chris., and Vogels, Godfried D. Role of Methanogens and Other Bacteria in Degradation of Dimethyl Sulfide and Methanethiol in Anoxic Freshwater Sediments. *Applied and Environmental Microbiology, Vol. 65, No. 5, p. 2116-2121, 1999.*

Matsuda, Akira., Ide, Tetsuo., and Fujii, Shozo. Behavior of Nitrogen and Phosphorus during Batch Aerobic Digestion of Waste Activated Sludge – Continuous Aeration and Intermittent Aeration by Control of DO. *Wat. Res. Vol. 22, No. 12, pp. 1495-1501, 1988.*

McCarty, Perry L., and Smith, Daniel P. Anaerobic Wastewater treatment. *Environ. Sci. Technol., Vol. 20, No. 12, 1986.*

Moen, G., Stensel H. David., Lepistö, Raghida., Ferguson, John F. Effect of Solids Retention Time on the Performance of Thermophilic and Mesophilic Digestion of Combined Municipal Wastewater Sludges. *Water Environment Research, Volume 75, Number 6, 2003.*

Müller, J. A. Prospects and problems of sludge pre-treatment processes. *Water Science and Technology, Vol. 44, No. 10, pp 121-128. 2001.*

Murthy, S. N., Forbes, B., Burrowes, P., Esqueda, T., Glindemann, D., Novak, J., Higgins, M. J., Mendenhall, T., Toffey, W., Peot, C. Impact of High Shear Solids Processing on Odor Production from Anaerobically Digested Biosolids. *Proceedings of the 75th Annual Water Environment Federation Technical Exposition and Conference, Chicago, Illinois, Water Environment Federation, Alexandria, Virginia, 2002.*

Neyens, E., and Baeyens, J. A review of thermal sludge pre-treatment processes to improve dewaterability. *Journal of Hazardous Materials B98, 51 – 67, 2003.*

Novak, John T. Dewatering of Sewage Sludge. *Drying Technology, 24: 1257-1262, 2006.*

Novak, John T., Verma, N., and Muller, C. D. The role of iron and aluminum in digestion and odor formation. *Water Science & Technology, Vol. 56, No. 9, pp. 59-65, 2007.*

Parravicini, V., Smidt, E., Svardal, K., and Kroiss, H. Evaluating the stabilization degree of digested sewage: investigations at four municipal wastewater treatment plants. *Water Science & Technology Vol. 53 No. 8 pp. 81-90, 2006.*

Parravicini, V., Svardal, K., Hornek, R., and Kroiss, H. Aeration of anaerobically digested sewage sludge for COD and nitrogen removal: optimization at large scale. *Water Science & Technology-WST, 57.2, 2008.*

Pickworth, B., Adams, J., Panter, K., and Solheim, O. E. Maximizing biogas in anaerobic digestion by using engine heat for thermal hydrolysis pre-treatment of sludge. *Water Science & Technology Vol. 54, No. 5, pp. 101-108, 2006.*

Sinkjær, O., Bϕgebjerg, P., Grüttner, H., Harremoës, P., Jensen, K.F., and Winther-Neilsen, M. External and internal sources which inhibit the nitrification process in wastewater treatment plant. *Wat.Sci.Tech. Vol. 33, No. 6, pp. 57-66, 1996.*

Tchobanoglous, G., Burton, F.L., Stensel, H.D. Wastewater Engineering: Treatment and Reuse. *Metcalf & Eddy Inc., 4th Ed., McGraw-Hill, New York, 2003.*

Tyagi, R. D., Tran, F. T., and Agbebavi, T. J. Mesophilic and Thermophilic Aerobic Digestion of Municipal Sludge in an Airlift U-Shape Bioreactor. *Biological Wastes 31, 251-266, 1990.*

U.S. EPA. Environmental Regulations and Technology - Control of Pathogens and Vector Attraction in Sewage Sludge. *EPA/625/R-92/013, 2003*.

Van Leerdam, Robin C., De Bok, Frank A. M., Lomans, Bart P., Stams, Alfons J. M., Lens, Piet N. L., and Janssen, Albert J. H. Volatile Organic Sulfur Compounds in Anaerobic Sludge and Sediments: Biodegradation and Toxicity. *Environmental Toxicity and Chemistry, Vol. 25, No. 12, pp. 3101-3109, 2006.*

Warner, A. P. C., Ekama, G. A., and Marais, G. V. R. The Activated Sludge Process – IV: Application of the General Kinetic Model to Anoxic-Aerobic Digestion of Waste Activated Sludge. *Wat. Res., Vol. 20, No. 8, pp. 943-958, 1986.*

Winther-Nielsen, Margrethe., and Jansen, Jes la Cour. The Role of Sludge in Nitrification Inhibition Tests. *Wat. Sci. Tech., Vol. 33, No. 6, pp. 93-100, 1996.*

Zhang, Tian C., and Noike, T. Influence of Retention Time on Reactor Performance and Bacterial Trophic Populations in Anaerobic Digestion Processes. *Wat. Res. Vol. 28, No. 1, pp. 27-36, 1994*.

2 ANAEROBIC DIGESTION OF THERMALLY HYDROLYZED SLUDGE

ABSTRACT

Sludge digestion has gained importance in recent year because of increasing interest in energy recovery and public concern over the safety of land applied biosolids. Many new alternatives are being researched for reducing excess sludge production and for more energy production. With an increase in solids destruction, the nutrients that are contained in sludge especially nitrogen, are released to solution and can be recycled as part of filtrate or centrate stream.

Nitrogen has gained importance because it has adverse effects on ecosystem's as well as human health. NH_4^+, NO_2^-, NO_3^-, and organic nitrogen are the different forms nitrogen found in wastewater. While ammonia is toxic to aquatic life, any form of nitrogen can be utilized by *cyanobacteria* and result in eutrophication. NO_2/NO_3, if consumed by infants through water, can affect the oxygen uptake capability. Hence, removal of nitrogen from wastewater stream before discharging is important.

The main purpose of this study was to evaluate the performance of the Cambi process, a thermophilic hydrolysis process used as a pre-treatment step prior to anaerobic digestion. Thermal hydrolysis, as a pre-treatment to anaerobic digestion increases the biological degradation of organic volatile solids and biogas production. The thermal hydrolysis process destroys pathogens and hydrolysis makes the sludge readily available for

digestion, while at the same time facilitating a higher degree of separation of solid and liquid phases after digestion.

Experiments were conducted in three phases for anaerobic digestion using the Cambi process as pre-treatment. The phases of study includes comparison of two temperatures for thermal hydrolysis (Cambi 150°C and Cambi 170°C), comparison of two solid retention times in anaerobic digestion (15 Day and 20 Day) and comparison of two mesophilic temperatures in anaerobic digestion (37°C and 42°C). Different experimental analyses were conducted in all the phases such as pH, bio-gas production, COD removal, VS destruction, nitrogen removal, odor and dewatering characteristics and the results are compared among all the phases.

2.1 Introduction

Anaerobic sludge digestion processes are biological processes used for stabilizing organic matter from primary and secondary waste water treatment and converting the organics to methane, a fuel which can be used to generate energy (McCarty *et al.,* 1986). Digestion reduces the total mass of solids, destroys pathogens, and makes it easier to dewater or dry the sludge (Grady *et al.,* 1999). Generally there are thought to be two optimum temperatures in anaerobic digestion, mesophilic (35° C) and thermophilic (55°C) (Cheol *et al.,* 1997).

As a result of the wide application of the waste activated sludge process, excess sludge generated by this process presents a serious disposal problem. Anaerobic digestion is the best available technique to prepare sludge for land application (Bougrier *et al.,* 2006).

However, this process cannot always be applied at all waste water treatment plants (WWTP) because of limited space. For some plants, the best solution for this is to minimize the footprint of the sludge treatment process. Thermal hydrolysis pre-treatment for waste activated sludge was developed to reduce the size of sludge digestion facilities (Chauzy *et al.,* 2005).

Thermal pre-treatment in the temperature range from 130^{o}C-180^{o}C destroys cell walls and makes the proteins accessible for biological degradation (Muller 2001). Results showed that thermal pre-treatment is suitable for stabilization of sludge, improving dewaterability of the sludge, reducing pathogens and increasing bio-gas production (Hariklia *et al.,* 2003). It has been shown that anaerobic digestion following thermal hydrolysis can consistently achieve 55% to 60% volatile solids destruction (Jolis 2008). Anaerobic digestion with thermal hydrolysis as a pre-treatment step provided good results in terms of VS removal, COD removal and biogas production and is one of the pertinent processes for activated sludge process available in the market (Camacho *et al.,* 2008).

The Cambi process is one type of thermal hydrolysis process (Neyens *et al.,* 2003). Raw sludge from the wastewater treatment process is dewatered to approximately 10-15% dry solids (DS) prior to thermal hydrolysis in order to reduce the volume of sludge going to the digester. The Cambi process breaks down the cells and generates soluble COD mainly in the form of volatile fatty acids, (VFAs) and this increases the digestibility of the sludge

(Pickworth *et al.,* 2006). The degree of stabilization shows that up to 60% of COD is converted to biogas and the stabilized sludge is free of pathogens (Kepp *et al.,* 2000).

Pickworth *et al.,* 2006, Jolis 2008, Kepp *et al.,* 2000, Camacho *et al.,* 2008 showed that the anaerobic digestion process with Cambi thermal hydrolysis process as pretreatment gave up to 60-70% of the volatile solids reduction, which is 10-20% higher than conventional digestion. Results showed 50% reduction of digester volume and 50% mass reduction due to better dewaterability. Adding a thermal hydrolysis step as pre-treatment to anaerobic digestion increases dewatered cake solids by 10-12% over conventional digestion.

Fjaergard (2001) conducted a pilot study in San Francisco during 2001-2003 on pre-treatment processes at high temperature for both mesophilic and thermophilic digestion. After nearly one year of operation he showed that, disturbances like pH, temperature and feeding rate that can strongly influence thermophilic digestion have little or no impact on mesophilic digestion.

2.2 Research Objectives

Previous research showed that the Cambi process as a pretreatment step to anaerobic digestion was successful in terms of higher biogas production, VS reduction, COD removal, odor removal and better dewaterability. However very little information is available in the literature on various operational parameters such as thermal hydrolysis temperature, anaerobic digestion temperature and SRT of the anaerobic digestion stage. The main purpose of this project was to evaluate the performance of the thermal hydrolysis process as a pre-treatment step prior to anaerobic digestion. The performance of anaerobic digesters was compared with a conventional mesophilic anaerobic digester. Three main conditions were investigated,

(a) Comparison of two mesophilic temperatures in anaerobic digestion, 37 and 42^{o}C.

(b) Comparison of two temperatures in the Cambi process 150 and 170^{o}C.

(c) Comparison of two solid retention times in anaerobic digestion 15 and 20 days.

The study was conducted in the Virginia Tech laboratories and the digesters were operated for approximately 15 months.

2.3 Methodology

Polyethylene batch fermentation conical shaped reactors supplied by Hobby beverage equipment Company (Temecula, California) were used as anaerobic digesters for this study. The volume of the vessel was 25L nominal volume. Initially the reactors were seeded with biosolids from the Ringsend Wastewater Treatment Works (Dublin, Ireland). Dewatered raw sludge cake (at a ratio of 50% primary and 50% secondary solids) at an approximate total solids concentration of 15% was collected from the DCWASA Blue Plains wastewater treatment plant and subjected to a thermal hydrolysis (Cambi process) at RDP Technologies, Inc. (Norristown, Pennsylvania). This hydrolyzed sludge served as feed to the anaerobic digesters. The solids concentration was 10-12% after thermal hydrolysis. The anaerobic digesters were operated at 37^{o}C and as continuosly stirred tank reactors. Three main operational variations were studied. These were:

(a) ***Comparison of two mesophilic anaerobic digestion temperatures 37°C and 42°C***

Two anaerobic digesters with Cambi processed sludge as feed were operated in the mesophilic temperature range (Cambi-MAD) with 15days SRT and 15 L active volume. The first one was operated at 37°C (Cambi MAD-37) and the second was operated at 42°C (Cambi MAD-42). The general setup for the digesters is shown in fig 2-1.

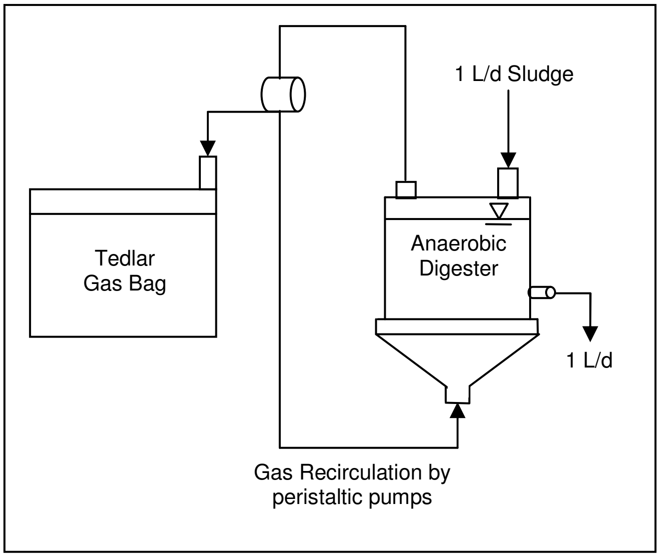


Figure 2-1: Schematic of comparison of two mesophilic temperatures an anaerobic digestion.

(b) ***Comparison of two hydrolysis temperatures in the Cambi process, 150°C and 170°C***

Two anaerobic digesters with Cambi processed sludge as feed were operated at 37°C and 15days SRT and 15 L active volume. Two Cambi process temperatures were chosen for this study. The first one was 150°C (Cambi THP-150-15D) and the second 170°C (Cambi THP-170-15D). The general setup for the digesters is shown in fig 2-1.

(c) ***Comparison of two solid's retention time in anaerobic digestion, 15days and 20 days***

Two anaerobic digesters were operated at 37°C and Cambi processed sludge at 150°C served as feed for both the digesters. The two digesters were maintained at different SRT's. One with 15 day SRT and 15 L active volume (Cambi THP-150-15D) and the second with 20 day SRT and 20 L active volume (Cambi THP-150-20D). The general setup for the digesters is shown in fig 2-1.

The table 2-1 shows the various digesters operated during the study and it also shows their SRT's, operating temperature and period of operation

Table 2-1: Anaerobic digester acronyms used during results analysis and operational characteristics.

Digester Acronym	SRT (days)	Operating Temperature (°C)	Period of Operation
Cambi MAD-37-15D	15	37	3 months
Cambi MAD-42-15D	15	42	3 months
Cambi THP-150-15D	15	37	1 year 3 months
Cambi THP-170-15D	15	37	8 months
Cambi THP-150-20D	20	37	6 months
Control MAD	20	37	18 months

All the digesters were kept in a constant temperature room at 37°C to maintain the temperature. The digester temperature was raised to 42°C using a thermolyte. Thermolyte is a device used for temperature adjustments. The thermolyte tape is wrapped to the digester and the temperature can be adjusted to 42°C. Peristaltic pumps (Cole parmer-600 rpm) were used to mix the gas in anaerobic digesters. The conical shape of the digester helped to provide effective mixing. The gas was recirculated from the head space to the bottom of the digester. The pumps were operated at 50% of their maximum speed. To maintain a constant SRT, 1 L of the sludge was taken out and 1 L of the feed was fed to the digester each day. The digesters were monitored for steady state based on pH, biogas and VS reduction. The daily biogas production of the anaerobic digesters was measured by connecting two tedlar gas bags of 40 L capacity to the digesters. The gas i.e., collected in gas bags is measured daily with Cole Parmer MasterFlex L/S peristaltic pump model no. 7555-90. The gas flow for this pump is calibrated as 0.973 L/min.

2.4 Analytical Methods

The biogas methane (CH_4) and carbon dioxide (CO_2) content collected in tedlar gas bags were analyzed using a Shimadzu Gas chromatograph GC-14A with a thermal conductivity detector (TCD). Helium was used as the carrier gas at a flow rate of approximately 17 ml/min. All the sludge analyses such as pH, COD, total solids, volatile solids, total Kjeldahl nitrogen (TKN) and ammonia were measured according to Standard Methods for the examination of Water and Waste Water (APHA 1998). For volatile fatty acids (VFAs) the samples were centrifuged in Beckman-Coulter Avanti-JE centrifuge at 10000 RPM for 30 min and then supernatant was filtered through 0.45µm filter (nitrocellulose disc filters, Fischer Scientific). The filtered samples were acidified with 85% phosphoric acid (H_3PO_4) before measurement. VFAs were measured using Shimadzu GC-14A Gas Chromatograph with Nukol Column and Flame ionization detector (FID). Helium was used as the carrier gas at a flow rate of approximately 17 ml/min. Other gases flow rates were, Nitrogen- 13 ml/min, Hydrogen-45 ml/min, Air-450 ml/min. A Shimadzu computer integrator CR501 chromatopak was used for data analysis. VFAs measured were acetic acid, propionic acid, butyric acid, isobutyric acid, valeric acid, isovaleric acid, heptanoic acid and caprionic acid.

CST, Optimum Polymer Dose and Odor

Generally anaerobic digestion is used to process sludge for land application, but research has shown that anaerobic digestion and dewatered biosolids cakes may generate unacceptable odors (Murthy *et al.,* 2002). The odor generation from the dewatered cake after anaerobic digestion was studied in the lab by using the method of Glindemann *et al* (2006), which is described in more detail below.

Optimum polymer dose plays very important role in the dewatering capability of sludge. The optimum polymer dose corresponds to the amount of polymer needed to attain the minimum capillary suction time (CST). One hundred mL of sludge was collected and cationic polymer (Polydyne Clarifloc 6288 1% w/w) was added and sheared in a Wearing blender for 30 seconds. The time to dewater this sample was measured using a CST apparatus (Triton 165, Triton 304-M) and a Whatman 17-CHR chromatography paper. The process was repeated until the lowest CST was obtained.

After the CST was determined, 400mL of sample was collected and conditioned using the cationic polymer dose which was found to be optimum. The sludge was then centrifuged in Beckman-Coulter Avanti-JE centrifuge at 10000 RPM for 30 min at 4^{o}C. The pellet was collected and further dewatered using a hydraulic piston press. The pellet was placed on Whatman 41 filter paper and pressed at a pressure of 39 psi for 15 minutes. The sludge cake obtained was broken in to small pieces. Five grams of cake was weighed and placed in a bottle. Triplicates of samples were prepared. The bottles were then sealed with a screw cap and Teflon-lined septa to prevent the loss of gas. The bottles were incubated over a period of 3 weeks at room temperature. Some samples also received bromo ethane sulfonic acid (BESA), the purpose of BESA addition is to inhibit methanogens. Methanogens convert organic sulfur compounds to sulfide. It they are inhibited, organic sulfur accumulates, so the organic sulfur with BESA can be considered to be the maximum organic sulfur potential. The samples with bromo ethane sulfonic acid (BESA) were also analyzed as it acts as methanogenisis inhibitor. 0.127 mM BESA is added to the odor bottle at bout 1-2 mL before capping. The cake total solids and volatile solids were measured to determine cake solid concentration as per the Standard Methods for the examination of Water and Waste Water (APHA 1998).

Organic Sulfur Analyses

The volatile organic sulfur compounds (VOSC's) were collected in the head space of the bottle. The contents of the bottle were analyzed for VOSC's (MT, DMS, DMDS) and H_2S using gas chromatography/mass spectrometry (GC 5890, MSD 5970) with a Supelco equity-5 column and 30m x 0.25 mm capillary column of film thickness of 1 µm. Twenty five µL of gas was collected from the syringe and inserted in to the inlet column. Liquid nitrogen was used as trap to obtain narrow peaks and for maximum separation of compounds.

2.5 Results and Discussion

The primary objective of this research was to evaluate the performance of anaerobic digestion with pretreatment by the Cambi process and compare the performance to a conventional mesophilic digester (control MAD) with a 20 day SRT. All the analyses were performed after determining that the digesters were at steady state. Steady state was determined by daily monitoring of pH, biogas production, solids removal and COD reduction. When little variation occurred in these parameters steady state was assumed. The performance of the anaerobic digesters was analyzed at steady state in each phase. The average values for measured parameters VS removal, COD removal for each phase at steady state are shown in figures 2-2, 2-3, 2-4 and 2-5.

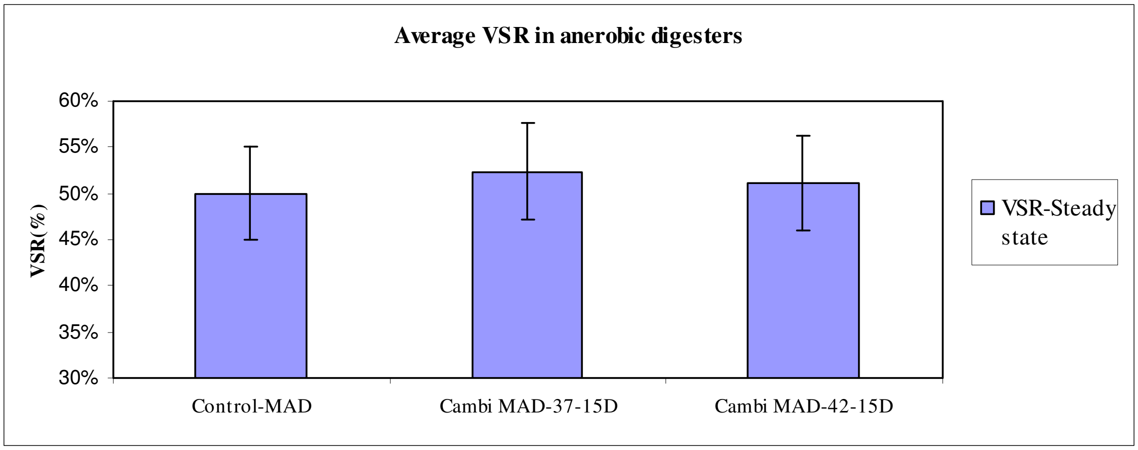


Figure 2-2: VSR values for anaerobic digesters during steady state (Operated about 2months).

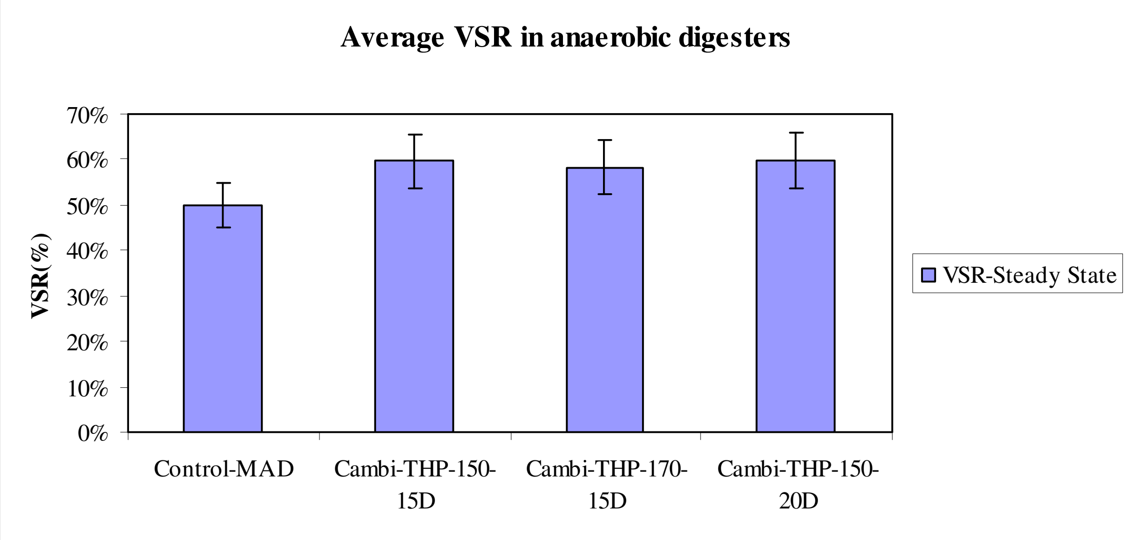


Figure 2-3: VSR values for anaerobic digesters during steady state (Operated-greater than 8 months).

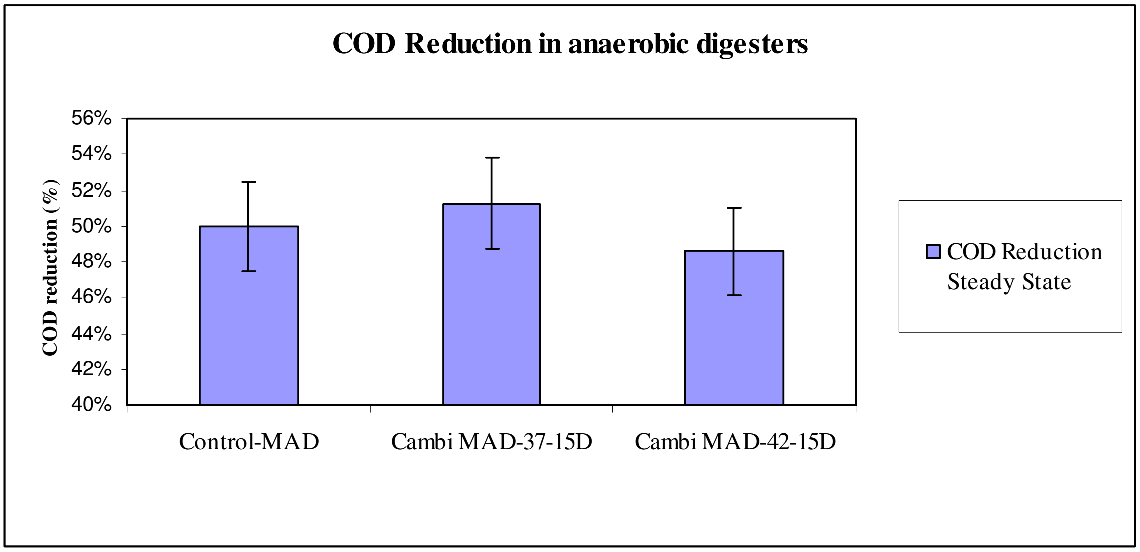


Figure 2-4: COD values for anaerobic digester in all phases during steady state (Operated about 2months).

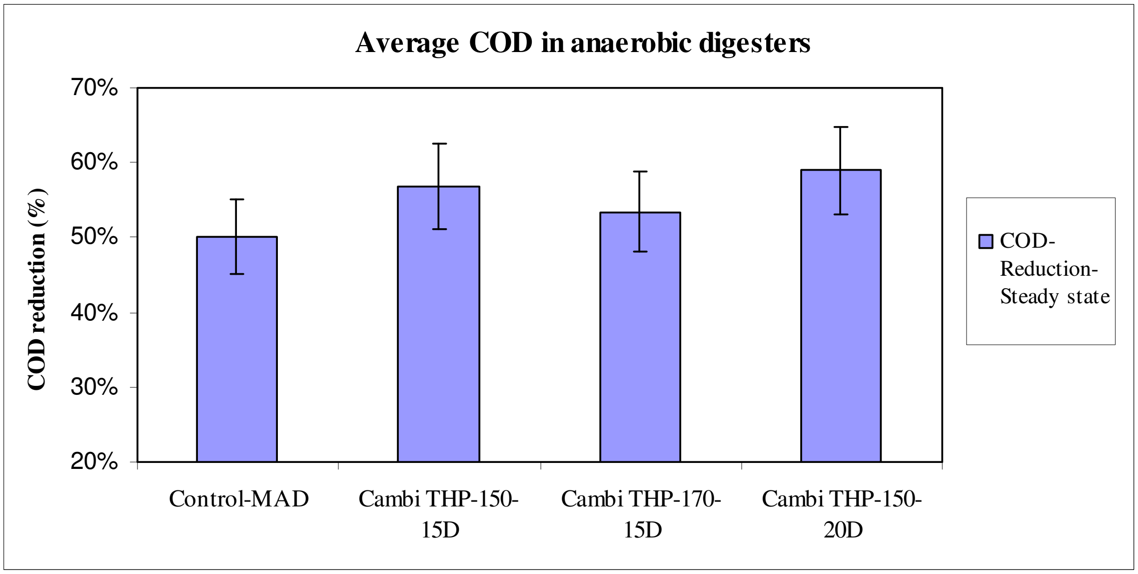


Figure 2-5: COD values for anaerobic digester in all phases during steady state (Operated-greater than 8 months).

VSR and COD reduction for figures 2-2 and 2-4 did not show greater variation because the period of operation was very less compared to other phases. Cambi MAD-37-15D was operated between June 2007 and September 2007 and Cambi MAD-42-15D was operated between October 2007 and December 2007. The data represents average value in this period. Cambi THP-150-15D and Cambi THP-170-15D were started in January 2008 and they were operated for longer duration. This was the main reason for the difference in VSR and COD reduction. The longer period of operation made the digesters acclimated and resulted in higher VSR and COD reduction. Overall data is discussed in later parts. The ammonia concentrations in Cambi MAD-37-15D and Cambi MAD 42-15D were also found to be less (discussed in later parts) during the first phase of operation but later they were increased as the days of operation increased.

Cambi MAD 37-15D and Cambi THP-150-15 D SRT were both same digesters; the VSR and COD reduction for Cambi THP-150-15D is greater because the period of operation is higher, this made the digester acclimated to the conditions and the VSR and COD reduction has gradually increased. Total VSR and COD data can be seen in figures 2-8 and 2-9.

Correlation between VS and COD for all the phases in anaerobic digestion

Biodegradability is generally expressed as a percentage of either COD removal or VS reduction. These characteristics change depending on the feed concentration. COD can be correlated with the VS of the sample, the relation being empirical. This ratio varies from sample to sample. For carbohydrates it is around 1.1, for lipids it is 2.9, for protein it is 1.5 (Spinosa *et al.,* 2001). This correlation is called as substrate/inoculum ratio and it is considered for prediction to methane production. Gonzalez-Fernandez *et al.,* 2009 studied various COD/VS ratios in anaerobic digestion on swine slurry and was able to conclude that COD/VS ratios have considerable effect on the process. He studied three different COD/VS ratios 1, 2 and 3 and showed that swine slurry degraded faster at COD/VS ratio of 1 compared to COD/VS ratio 2 and 3.

Figures 2-6 and 2-7 shows the correlation between VS and COD for all the phases in anaerobic digestion. There is a better correlation for the effluent compared to that of feed. The reason for this was the variations in the feed composition and concentrations that were shipped from the Blue Plains waste water treatment plant. At times the feed was very thick as high as 12-13% and at times it was around 9-10% total solids concentration. It was thought that the variation in solids could be due to variations in the Cambi process and the ratio of primary to secondary sludge.

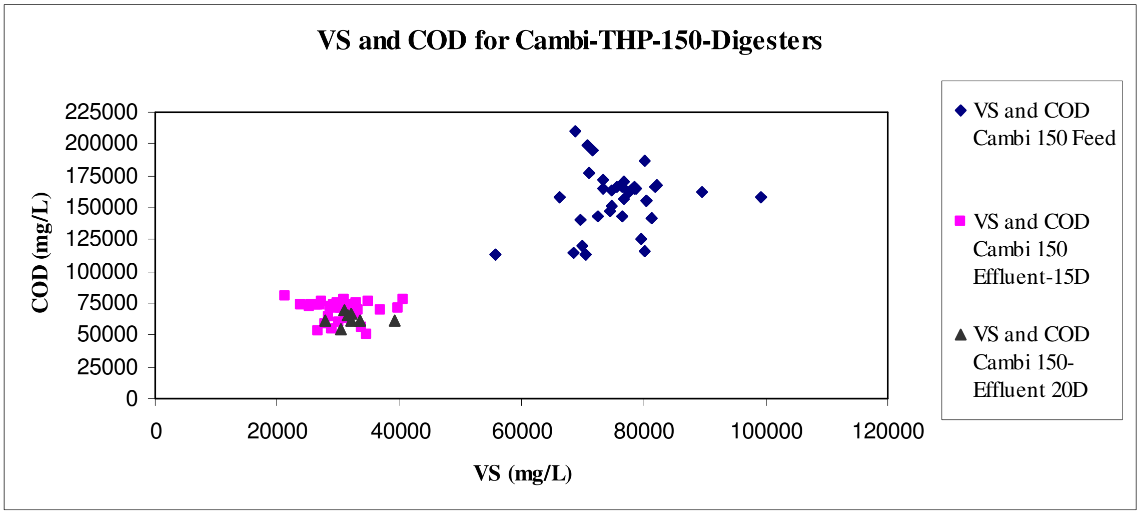


Figure 2-6: Correlation between VS and COD for Cambi THP-150 anaerobic digester.

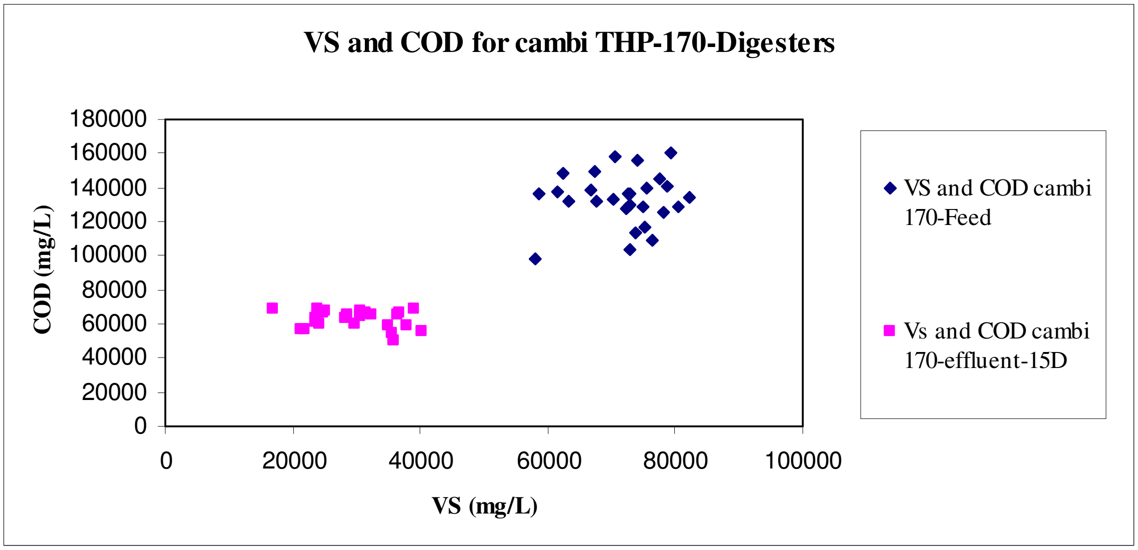


Figure 2-7: Correlation between VS and COD for Cambi THP-170 anaerobic digester.

More variations are seen in VS than COD. This is mainly because VS test may be more variable due to volatilization of VFA's and ammonium bicarbonate.

Table 2-2 shows the COD/VS ratios for all the phases

Table 2-2: Average COD/VS ratios for feed and effluent in anaerobic digesters.

Type	COD/VS
Cambi-THP 150 Feed	2.10
Cambi-THP 170 Feed	1.86
Cambi-THP 150-15D-MAD-37	2.28
Cambi THP 170-15D-MAD37	2.11
Cambi THP 150-20D-MAD-37	2.02
Control MAD	1.38

COD/VS ratio should be maintained efficiently for the control over process. The average COD/VS ratio for all the phases is shown in the Table 2-2. The general equation for oxygen demand of biomass can be written as:

$$C_5H_7O_2N + 5O2 \longrightarrow 5CO_2 + 2H_2O + NH_3$$

The COD/VS ratio for this equation was 1.42 COD/VS (Rittman, McCarty 2001). COD/VS ratio for Control-MAD was 1.38 (Banjade 2008). These higher ratios suggest that both Cambi pretreated sludge (Feed) and the anaerobic digesters effluent are of high proteins and lipids. Ratios vary considerably from process to process and these ratios suggest that the anaerobic digestion with Cambi pretreated sludge operated successfully at these COD/VS ratio.

pH

The optimum pH of the anaerobic digestion is 6.8-8.5 (Tchobanoglous *et al.,* 2003). The methanogenic activity will slow considerably with pH less than 6.3 and higher than 7.8 and this will inhibit the biogas production (Leitao *et al.,* 2006). A lower pH will result in inhibition of methanogens and a high pH results in the buildup of ammonia (Grady *et al.,* 1999).

The pH of Cambi MAD-37-15D and cambi MAD-42-15D were 7.86±0.07 and 7.82±0.05 ($x \pm \mu$) respectively. The data of pH is shown in the figure 2-8. The pH of other phases i.e., Cambi THP-150-15D, Cambi THP-170-15D, Cambi THP-150-20D were 7.84±0.12, 7.81±0.10, 7.73±0.06 respectively. The pH in Cambi THP-150-20D was less compared to Cambi THP-150-15D. The main reason for this was attributed as ammonia stripping in Cambi THP-150-20D. During the gas recirculation it was thought that the ammonia was stripped into the gas bags. The ammonia concentration in Cambi THP-150-20D was also lower than Cambi THP-150-15D. The gas recirculation in the anaerobic digesters helps to maintain the pH constant without much variation.

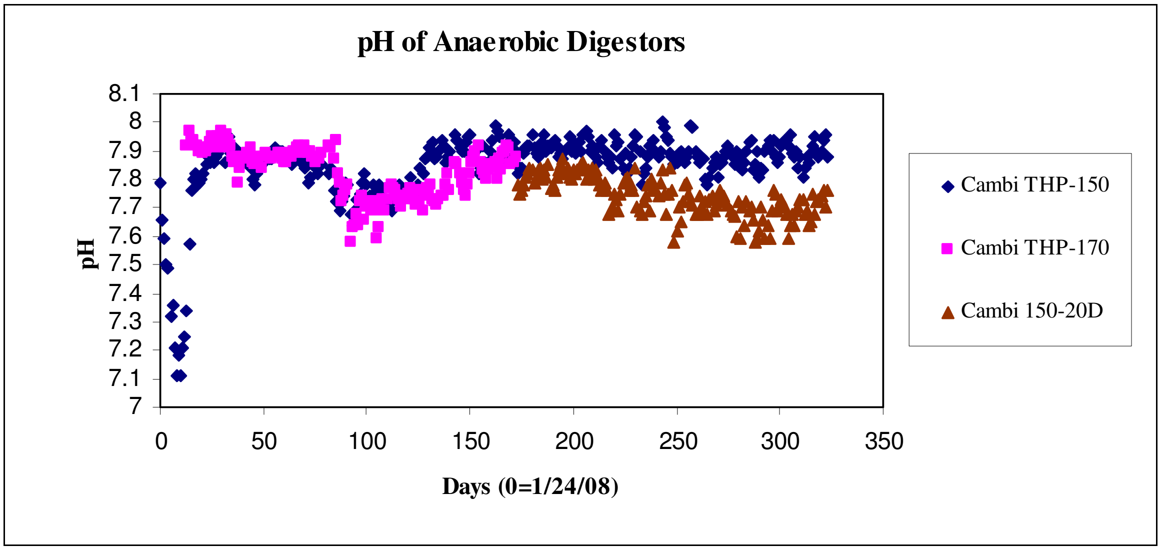


Figure 2-8: pH of mesophilic anaerobic digesters.

pH was maintained constant for all the phases as variations may cause inhibiting effect to the digesters. The values oh pH shows the acceptable range of anaerobic digestion. Anaerobic digesters were operated in the pH range of 7.5-7.8.

Volatile Solids Reduction (VSR)

Volatile solids were measured as the weight loss after the ignition (550^{o}C). There are a lot of speculations about this test as it is not considered to give actual volatile solids destruction, because the volatile fatty acids and NH_3 part may also volatilize during solids drying (Wilson *et al.,* 2008). The variation in VSR data shown in figure 2-9 is considered mainly because of variations of feed total solids concentrations that have been shipped from Blue Plains wastewater treatment plant. The feed concentrations varied from 10-15% total solids. The average VS reduction for Cambi MAD-37-15D and Cambi MAD-42-15D were 52.4% and 51.05%. The average VS reduction for other phases Cambi THP-150-15D, Cambi THP-170-15D and Cambi THP-150-20D were 58.8%, 58.2%, 59.8% respectively. The average total solids for Cambi THP-150 sludge were ~10.5%

and for Cambi THP-170 sludge it was ~10%. As discussed previously, the low VSR in Cambi MAD-37-15D was operated from June 2007 to September 2007 and Cambi MAD-42-15D was operated between October 2007 to December 2007 and this lower period of operation resulted in lower VSR. The digesters Cambi THP-150-15D and Cambi THP-170-15D were started in January 2008 and operated for longer duration and the digester had sufficient time to get acclimated to ammonia concentrations.

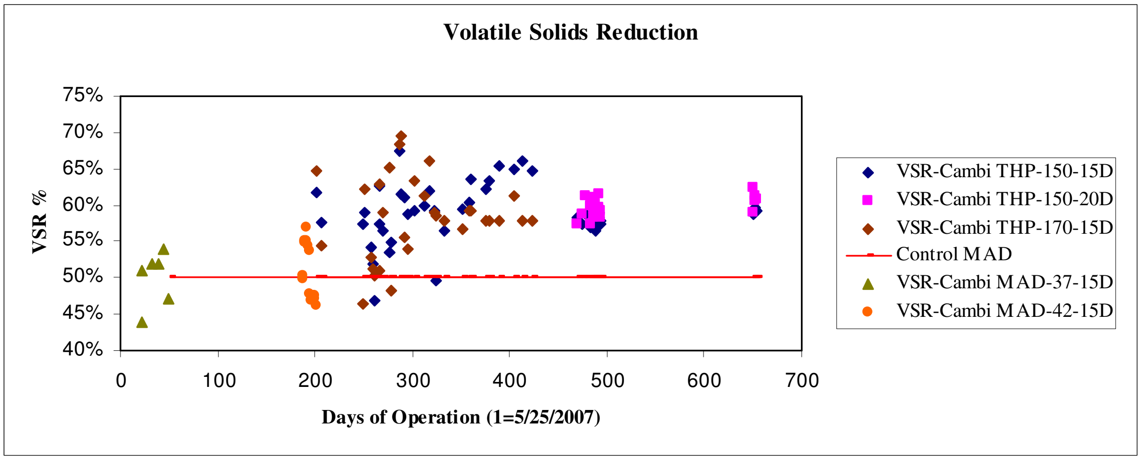


Figure 2-9: Volatile solids reduction of anaerobic digesters.

The reasons for higher variations in the data are mainly attributed to two major factors, the higher variations in the feed concentrations and the digesters getting acclimated. The VSR increased steadily and it reached a constant after certain period of operation (400-500 days). The VS reduction for control-MAD was 50% (Banjade 2008). The VS reduction for anaerobic digesters with Cambi processed sludge in all the phases is considerably higher. The VS reduction for Cambi MAD-37 is higher than Cambi MAD-42. The VS reduction for Cambi THP-150-15D was found to be higher than Cambi THP-170-15D but VS reduction for Cambi THP-150-20D was higher compared to all the phases. The higher SRT was considered as the most probable reason for more organics destruction. These results from the anaerobic digesters from all phases were similar initial results of high solid anaerobic digestion process from various researchers Pickworth *et al.,* 2006, Jolis 2008, Kepp *et al.,* 2000, they were able to achieve 60-70% of the volatile solids reduction, which is 10-20% higher than conventional digestion.

COD reduction

The Cambi process as pretreatment to anaerobic digestion improved COD reduction in a manner similar to VS reduction data. The overall COD reduction data is shown in the figure 2-10. The average COD reduction for Cambi MAD-37-15D and Cambi MAD-42-15D were 51.25% and 48.6% respectively. The average COD reduction for the other phases Cambi THP-150-15D, Cambi THP-170-15D and Cambi THP- 150-20D were 55.6%, 52.7%, and 58.5% respectively. As discussed previously the low VSR in Cambi MAD-37-15D and Cambi MAD-42-15D was because this was in the initial operation period June 2007 to September 2007 and it was thought that the digesters are not acclimated to high ammonia levels. Cambi THP-150-15D and Cambi THP-170-15D were initiated in January 2008 using the seed from other digesters and were operated for longer duration and the digester had sufficient time to get acclimated to ammonia concentrations. The variations in COD values were very high because of higher dilutions up to 1:500 and possibly because of insufficient digestion times. COD values for both the feeds were very high. For Cambi THP-150-15D sludge it was 160,000 mg/L and for Cambi THP-170-15D sludge it was 135,000 mg/L.

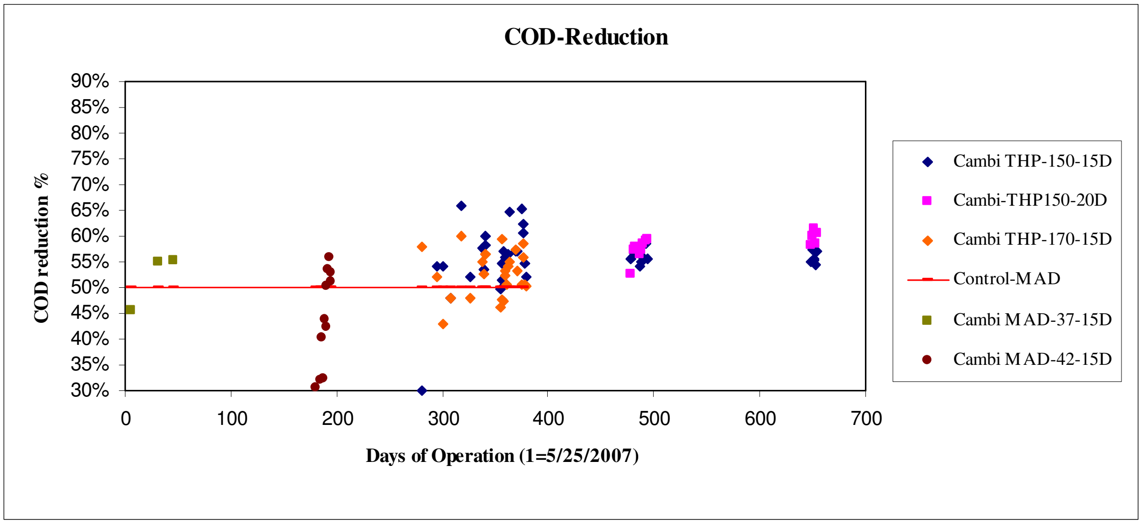


Figure 2-10: COD reduction of anaerobic digesters.

The Chemical oxygen demand (COD) decreases with an increase in the amount of methane produced (Grady *et al.,* 1999). The higher COD reduction corresponds to higher methane production in Cambi anaerobic digesters. The COD reduction for the control-MAD was 50% (Banjade 2008) and the VS reduction for the anaerobic digesters with Cambi pretreated sludge in all the phases was considerably higher. The COD reduction for Cambi THP-150-15D was higher than Cambi THP-170-15D and the COD reduction for Cambi THP-150-20D was higher because of the higher SRT.

The soluble COD values are shown in the figure 2-11. The average soluble COD values for Cambi THP-150-15D and Cambi THP-150-20D were 11680 mg/L and 11708 mg/L. The total VFAs anaerobic digesters were measured around at 6000 mg/L as HAC for all the phases. From the equation $CH_3COOH + 2O_2 \longrightarrow 2CO_2 + 2H_2O$, it can be calculated that 60 mg/L VFA's as HAC is equivalent to 64 mg/L as COD.

This shows that ~52% of the soluble COD is accounted for VFAs and this COD is thought be removed by introducing an aerobic digester downstream.

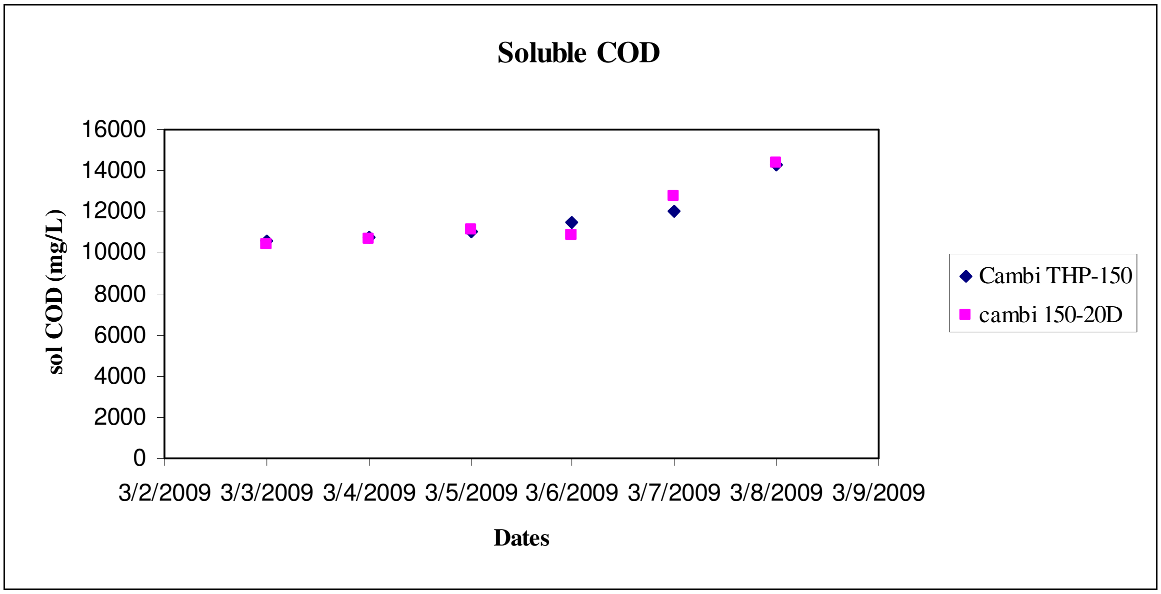


Figure 2-11: Soluble COD of anaerobic digesters.

Biogas Production and Composition

Anaerobic digestion benefit lies in the production of biogas because the gas can be used as an energy source. The main composition of biogas is methane (CH_4) and carbon dioxide (CO_2). The methane content in the biogas corresponds to the stability and the performance of the anaerobic digester as it reflects the amount of organic matter degraded (Grady *et al.,* 1999). The main advantages of the Cambi process as pretreatment lies in increasing biogas production and reduced the digester volume. The degree of stabilization shows that 60% of the COD is converted to biogas and the stabilized sludge is free of pathogens (Kepp *et al.,* 2000).

The CH_4 and CO_2 percentages in the anaerobic digester for Cambi for all the phases are shown in table 2-3. The values are average values over a period of 6 months.

Table 2-3: Gas composition of anaerobic digesters.

Sample	Methane Content (% by Volume)	CO2 Content (% by Volume)
Cambi MAD-37-15D	66.7 ± 2.5	NA
Cambi MAD-42-15D	65.2 ± 1.8	NA
Cambi THP-150-15D	60.9±1.90	34.3±1.14
Cambi THP-170-15D	59.4±1.03	35.9±1.63
Cambi THP-150-20D	61.34±1.03	34.6±0.58

The total gas production in Liters is shown in figure 2-12. The average total gas production for Cambi MAD-37-15D and Cambi MAD-42-15D were 11.5 L/g VS destroyed and 12.1 L/g VS destroyed. The average gas production for other phases Cambi THP-150-15D, Cambi THP-170-15D and Cambi THP-150-20D were 18 L/g VS destroyed, 17.6 L/g VS destroyed and 19.9 L/g VS destroyed respectively.

Methane and CO_2 percentages are shown in table 2-3. The methane percentage for the later phases Cambi THP-150-15D, Cambi THP-170-15D, Cambi THP-150-20D decreased when compared to initial stages Cambi MAD-37-15D and Cambi-MAD-42-15D, this was mainly because of the change in microbial activity in the anaerobic digester. The archaea community (Aceticlastic methanogens and hydrogen oxidizing methanogens) in the anaerobic digester varied during the operation. It is thought that there is shift in the dominance of these archaea and this resulted in lower methane content for later stage.

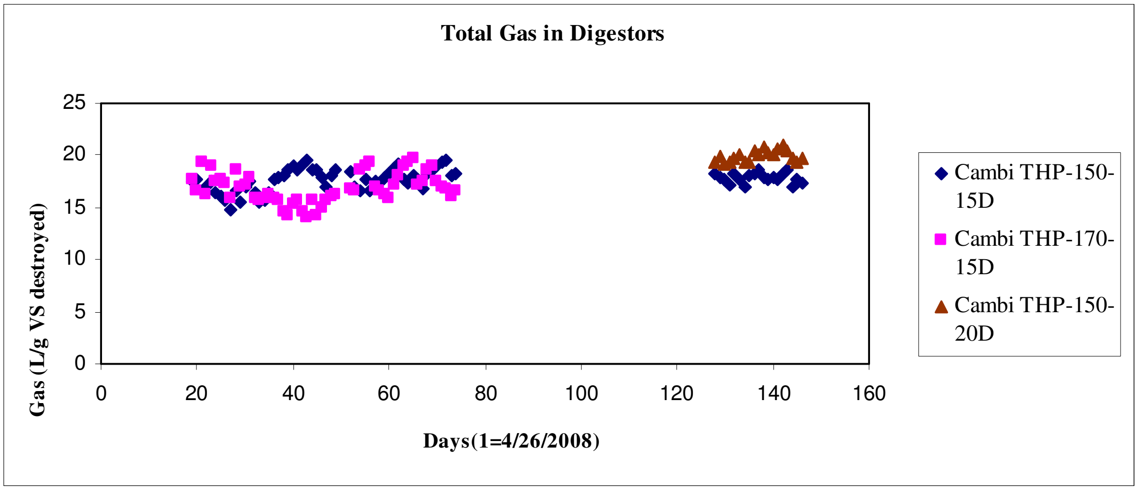


Figure 2-12: Total gas production in anaerobic digester.

The total biogas production of Cambi THP-150-15D was higher than Cambi THP-170-15D and the biogas production for Cambi THP-150-20D was higher among all the phases. The biogas data is consistent with the COD reduction data.

Ammonia and TKN

Anaerobic digestion degrades protein and this result in the accumulation of ammonia while degrading organic matter (Grady *et al.,* 1999). The ammonia in anaerobically digested sludge can increase the nitrogen load to the plant if centrate is recycled. The average values for ammonia are shown in the table 2-4. Efforts were made to reduce this ammonia buildup in the anaerobic digester by operating an aerobic digester downstream.

Table 2-4: Average ammonia for anaerobic digesters.

Sample	**Ammonia mg/L as N**
Cambi MAD-37	1730 ± 80
Cambi MAD-42	2280 ± 170
Cambi THP-150-15D	2508±84
Cambi THP-170-15D	2467±130
Cambi THP-150-20D	2128±426
Cambi THP-150-Feed	535±65
Cambi THP-170-Feed	550±45

All the ammonia analyses were performed at steady state for the anaerobic digester. Figure 2-13 shows overall ammonia values. The variations in the ammonia concentration were thought to be due to change in feed characteristics. Cambi THP-150-20D had lower ammonia concentrations compared to other digesters, the main reason for this was due to ammonia stripping by the gas recirculation system. The ammonia was stripped into the gas bag and mixed with biogas. The pH was also lower in the Cambi THP-150-20D compared to other digesters, supporting this ammonia stripping.

$NH_4^+ \longrightarrow NH_3 + H^+$

The H^+ ions are released because of ammonia stripping and this is the reason for decrease of pH.

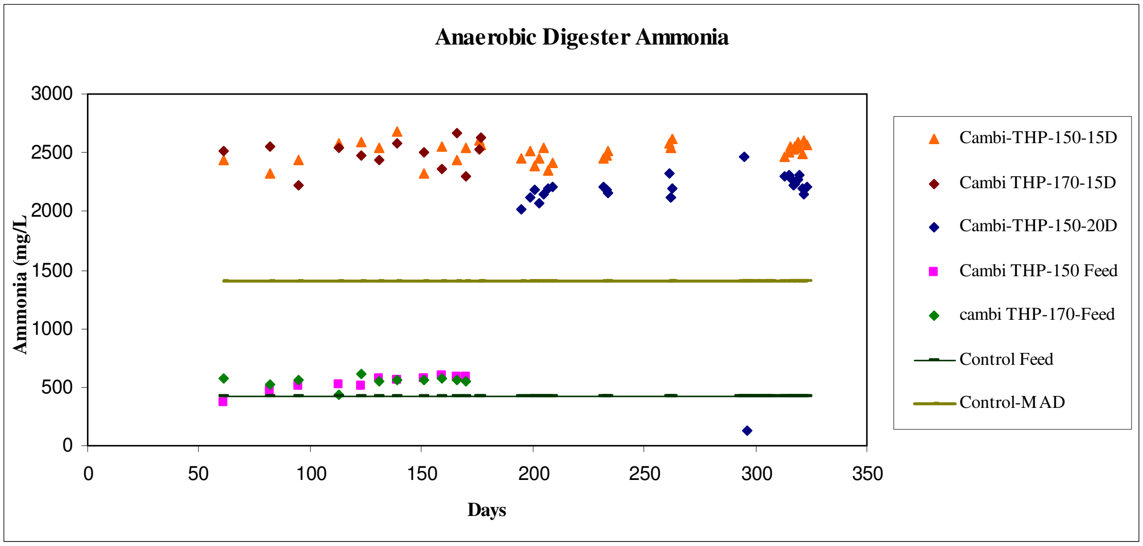


Figure 2-13: Ammonia present in feed and effluent of the anaerobic digesters.

The average ammonia for the feed to the control was 420 mg/L and the ammonia in treated sludge control-MAD was 1400 mg/L (Banjade 2008). This shows that Cambi pretreatment greatly increases the ammonia levels during anaerobic digestion. The effluent from the anaerobic digester resulted in high ammonia concentrations for all the phases of close to 2500 mg/L as N. The average ammonia concentration for Cambi THP-150-20D was 2200 mg/L, due to gas stripping. The feed ammonia concentration for both the feeds was nearly 500 mg/L as N and they did not vary. The ammonia concentrations for Cambi MAD-37-15D and Cambi MAD-42-15D were lower than all other phases and had clear difference about of 600 mg/L. Because VS & COD reduction was lower, less ammonia was produced.

Total Kjeldahl Nitrogen (TKN) is the sum of organic nitrogen, ammonia (NH_3) and ammonium (NH_4^+). The average values for the TKN are shown in table 2-5. TKN values for feed and effluent were similar for all the phases, operating all these phases and this is expected. TKN values for Cambi THP-150-20D were less than Cambi THP-150-15D, this is consistent with the ammonia data.

Table 2-5: Average TKN values for feed and effluent of anaerobic digesters.

Sample	**TKN (mg/L)**
Cambi THP-150-Feed	5822
Cambi THP-170-Feed	5656
Cambi THP-150-15D	5292
Cambi THP-170-15D	4267
Cambi THP-150-20D	5204

Volatile Fatty Acid Production and Consumption

VFA’s are formed as intermediates during acidogenisis in anaerobic digestion. Accumulation of VFAs result from overloading or inhibition of the Aceticlastic methanogens especially from high ammonia levels (Leitao *et al.,* 2006). Volatile fatty acids are weak acids that are dissociated at neutral pH (Grady *et al.,* 1999). The presence of high VFAs is detrimental to methanogenic activity through the toxic action of un-ionized VFAs. It is always beneficial to maintain favorable pH and moderate VFA concentration so that no inhibitory effects are imposed on the system (Cohen *et al.,* 1982).

VFAs were measured in both the feed as well as the effluent to assess the performance of the anaerobic digester. Because of Cambi pretreatment, the hydrolyzed sludge result in higher VFA’s in the feed. The amount of VFA’s removed after anaerobic digestion was analyzed. Table 2-6 shows the feed and effluent VFA’s. The average total VFA’s are shown in figure 2-14 and individual VFA’s were shown in figure 2-15. All the VFA’s were analyzed as mg/L as HAC.

Table 2-6: VFA's for Feed and Effluent in different phases.

VFA's	Feed (mg/L)	Effluent (mg/L)
Cambi THP-150-15D	30000	6175
Cambi THP 170-15D	34950	4250
Cambi THP-150-20D	30000	3230

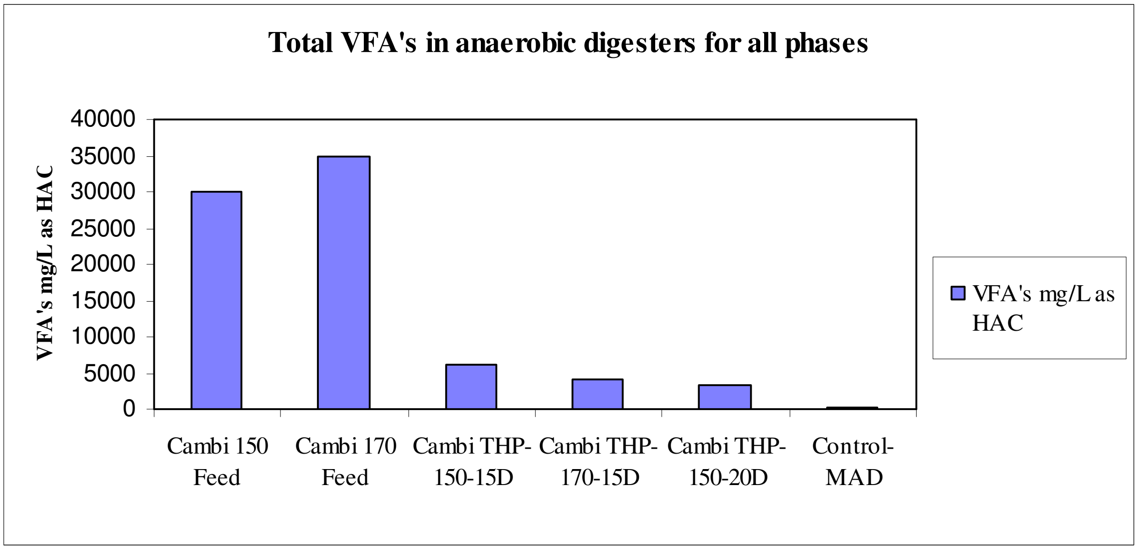


Figure 2-14: Total VFA's in the anaerobic digesters for all phases.

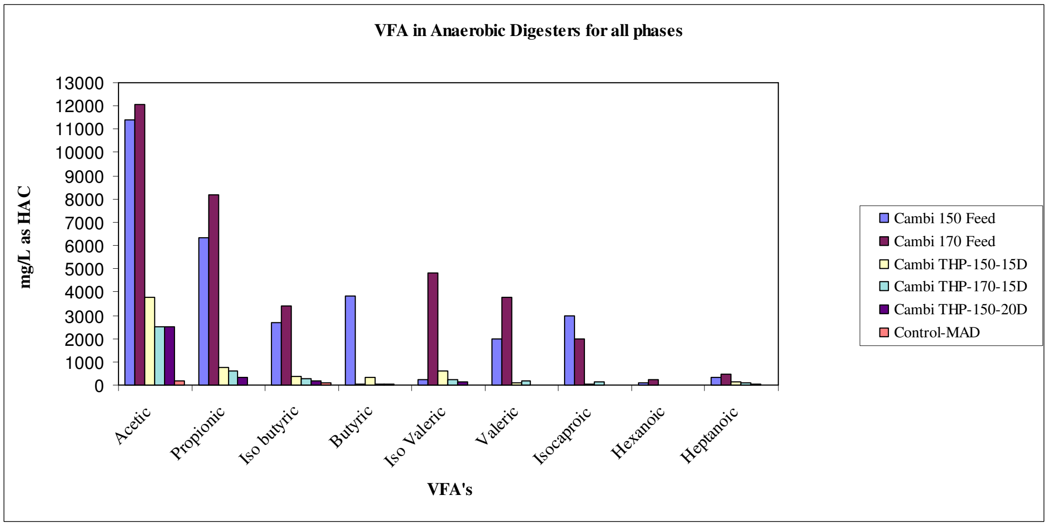


Figure 2-15: VFA's in the anaerobic digesters for all phases, Control-MAD also included.

The data shows that the Cambi pretreatment result in very high VFA's compared to conventional anaerobic digestion. The VFA's removal in Cambi THP-150-20D was greater than the VFA's removal in Cambi THP-150-15D, this was mainly due to the longer SRT. Longer SRT gives more time for microbes for destruction of organics. The values show that the anaerobic digestion occurred efficiently with hydrolysis and acidogenisis at proper rate.

Optimum Polymer Dose and Cake Solids concentration

Polymer dose and cake solids concentration experiments were conducted on the anaerobic digesters after they attained steady state. Figure 2-16 shows the polymer dose for Cambi THP-150-15D, Cambi THP-170-15D and Cambi THP-150-20D. The optimum polymer dose is lower for Control-MAD compared to all the phases in anaerobic digestion of Cambi pretreated sludge. The optimum polymer dose for Cambi THP-170-15D is less compared to Cambi THP-150-15D and Cambi THP-150-20D.

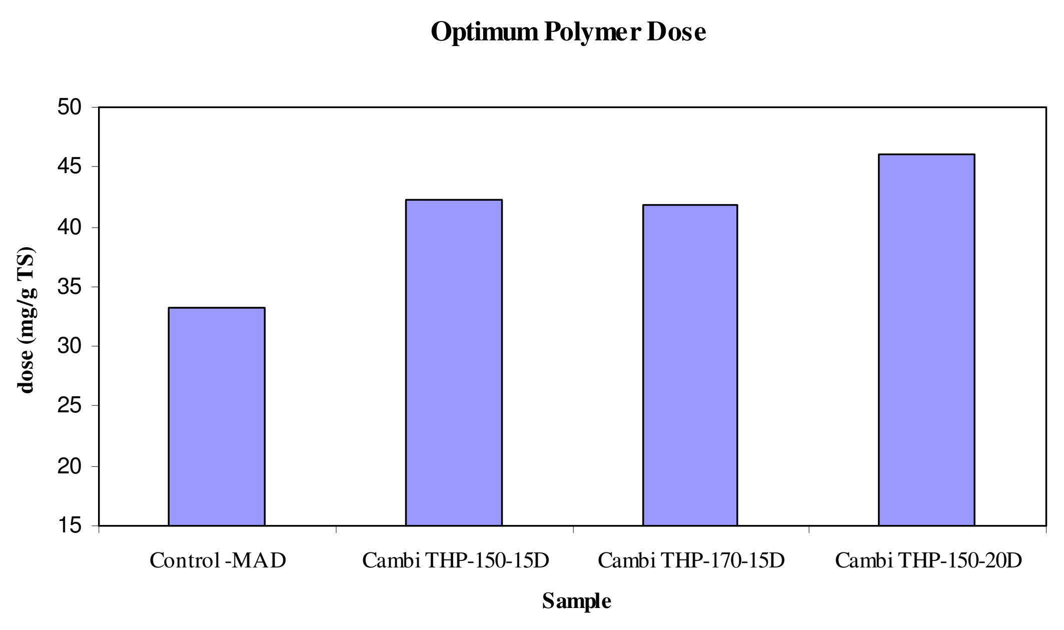


Figure 2-16: Optimum polymer dose for the anaerobic digesters.

The cake solids concentration is shown in the figure 2-17. The concentration of cake solids completely depends upon the sludge characteristics. The cake solids concentration for the Control-MAD was 20% and is much lower than for the Cambi pretreated anaerobic digestion. A major advantage of Cambi pre-treatment to anaerobic digestion is seen from high cake solids concentration. Cambi THP-150-15D resulted in total cake solids concentration as 40%, where as Cambi THP-170-15D resulted in 36% and Cambi THP-150-20D resulted in 35.6%. These results showed higher cake solids concentrations which were similar to the work performed by Pickworth *et al.,* 2006 and Kepp *et al.,* 2000. Anaerobic digestion with Cambi pre-treatment resulted in higher cake solids concentration compared to conventional anaerobic digestion. This was mainly because of the Cambi process mechanism which involves centrifugation of primary and secondary blended sludge.

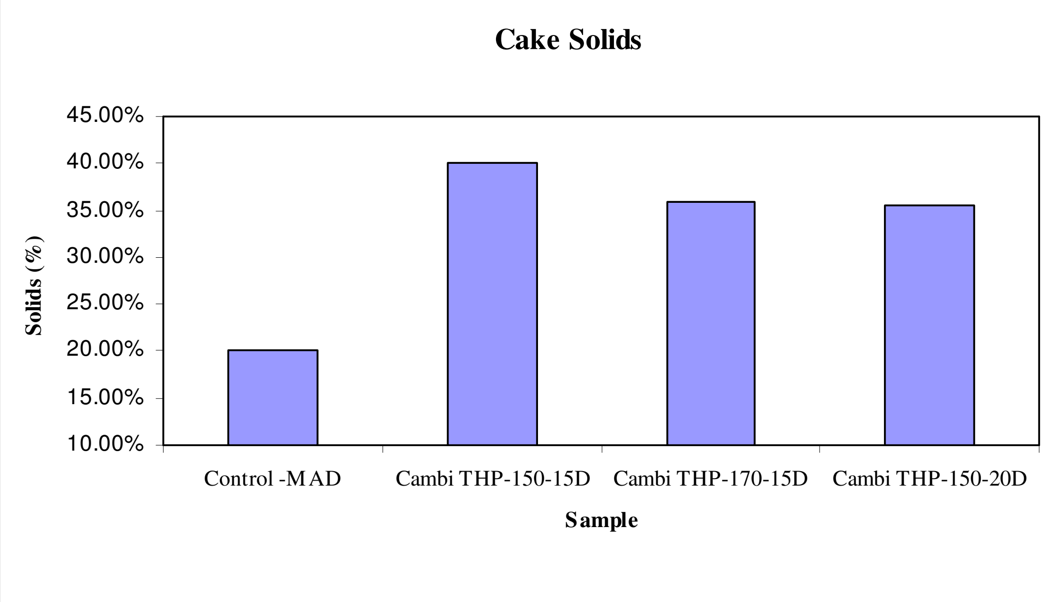


Figure 2-17: Cake solids concentration for anaerobic digesters.

Odor Analyses

Biosolids may be malodorous as well as be of concern with regard to public health (De Michele *et al.,* 2000). Odorous emissions from sewage systems and WWTP's can cause serious problems in the vicinity of the plant. Odorants present in the liquid phase are emitted into the ambient air at the liquid-gaseous interface (Frechen *et al.,* 1998).

The main odor causing chemicals were found to be volatile inorganic sulfur compounds and volatile organic sulfur compounds (VOSC) which include carbon disulfide, hydrogen-sulfide (H_2S), methanethiol (MT), and dimethyl sulfide (DMS), dimethyl disulfide (DMDS) and trimethyl amine. A better understanding is required concerning the generation of these odors; whether they are generated immediately after dewatering or slowly over a number of days following dewatering. Methanogens play a key role in the degradation of VOSC's (Novak *et al.,* 2006, Higgins *et al.,* 2006, Kim *et al.,* 2002). Van Leerdam *et al.,* (2006) studied the degradation and toxicity of VOSC's in sludge. They found that all samples degraded MT, DMS, and DMDS anaerobically. In the presence of sulfate and BESA, degradation of these compounds was coupled to sulfate reduction.

Novak *et al.,* (2006) studied anaerobically digested sludge and dewatered sludge cake, and found that primary VOSC's MT, DMS, DMDS followed a predictable pattern of production, peaking between day 1 and day 7, and then the declining started. DMDS peaked early and the magnitude was very low. After the conversion of MT and DMS to H_2S, the sulfide in the anaerobic sludge cake precipitated as FeS (Higgins *et al.,* 2006). Total volatile organic sulfur concentration (TVOSC) peak measured with addition of bromo ethane sulfonic acid (BESA) can be considered to be the odor generation potential of the cake (Higgins *et al*., 2006).

The important mechanisms in the formation of VOSC's are found to be biodegradation of sulfur containing amino acids, cysteine and methionine to form H_2S and MT, methylation of H_2S and MT to form MT and DMS and oxidation of MT to form DMDS. Cambi Pretreatment reduced odors greatly during anaerobic digestion. The reason for this is a variation in the VOSC's produced. Anaerobic digestion with Cambi pretreatment changed the mechanism of VOSC's production. Process resulted in more of DMS and DMDS instead of forming MT. It is also thought that the genre of sulfate reducing bacteria varied because of Cambi pre-treatment. Volatile organic sulfur compounds (VOSC's) were measured for Cambi THP-150-15D, Cambi THP-150-20D and Cambi THP-170-15D with and without addition of BESA. Figures 2-18, 2-19, 2-20 and 2-21 show the peak TVOSC data and overall odor data. The peak total volatile organic sulfur compounds (TVOSC) odors for anaerobically digested sludge with Cambi pretreatment were very low compared to conventional anaerobic digestion. The peak TVOSC for conventional anaerobic digestion was 788 ppmv as S/g VS (Banjade 2008), whereas peak TVOSC for cambi THP-150-15D was 101 ppmv as S/g VS, for Cambi THP-150-20D was 70 ppmv as S/g VS and cambi THP-170-15D was 111 ppmv as S/g VS. The samples with BESA added showed greater TVOSC, this is due to methanogenisis inhibition by BESA. Anaerobically digested sludge under mesophilic conditions without addition of BESA gave the peak within 2 days, while the same sludge with addition of BESA gave the peak after 6 days. The data also supports the work done by Higgins *et al.,* 2006 and shows the role of methanogens in the odor removal. Previous research showed that anaerobic digestion cannot remove odors completely from digested effluent, one of the major conclusions that can be drawn from this study was that the Cambi pretreatment greatly reduces the odors compared to conventional anaerobic digestion.

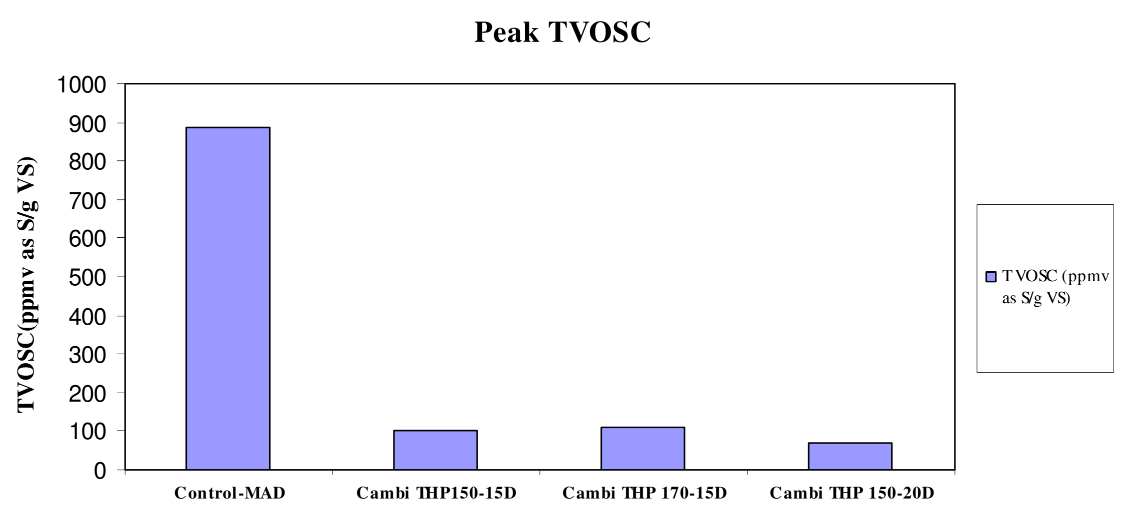


Figure 2-18: Peak TVOSC values for anaerobic digesters, without BESA.

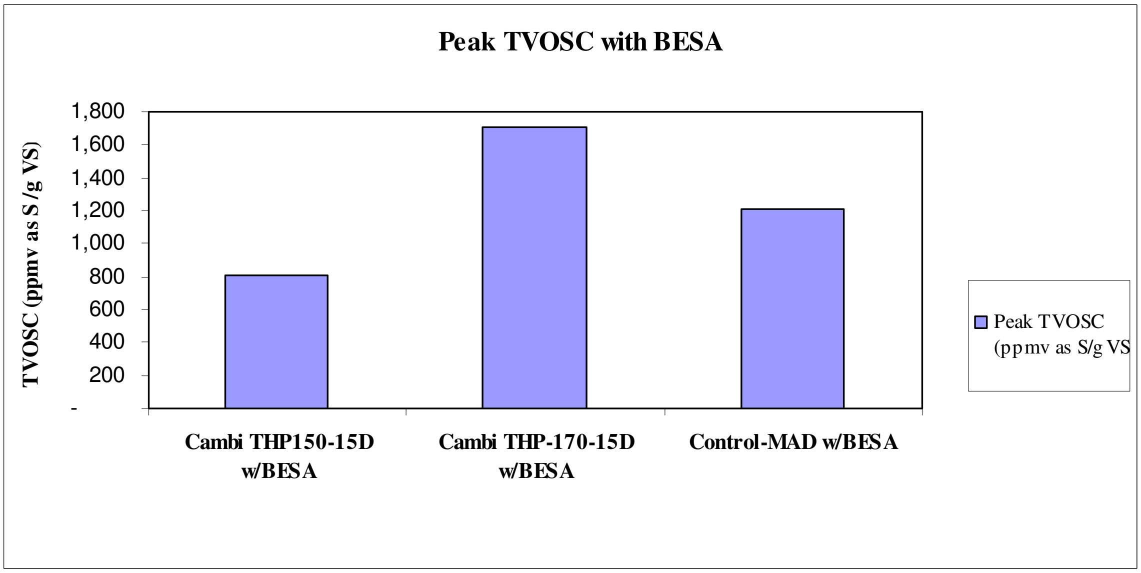


Figure 2-19: Peak TVOSC values for anaerobic digesters, with BESA.

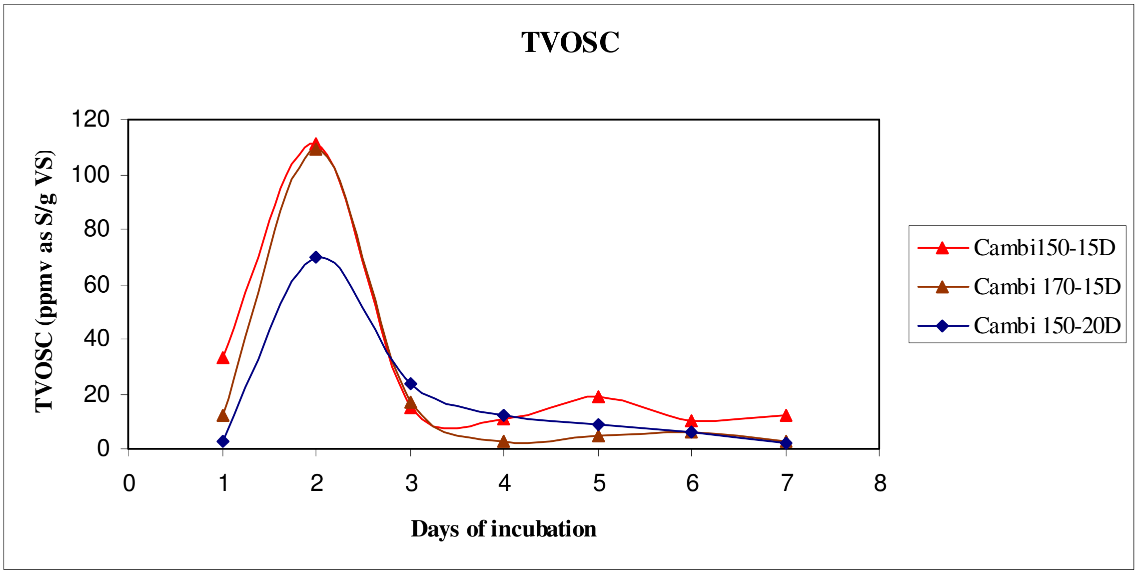


Figure 2-20: TVOSC values for anaerobic digesters, without BESA.

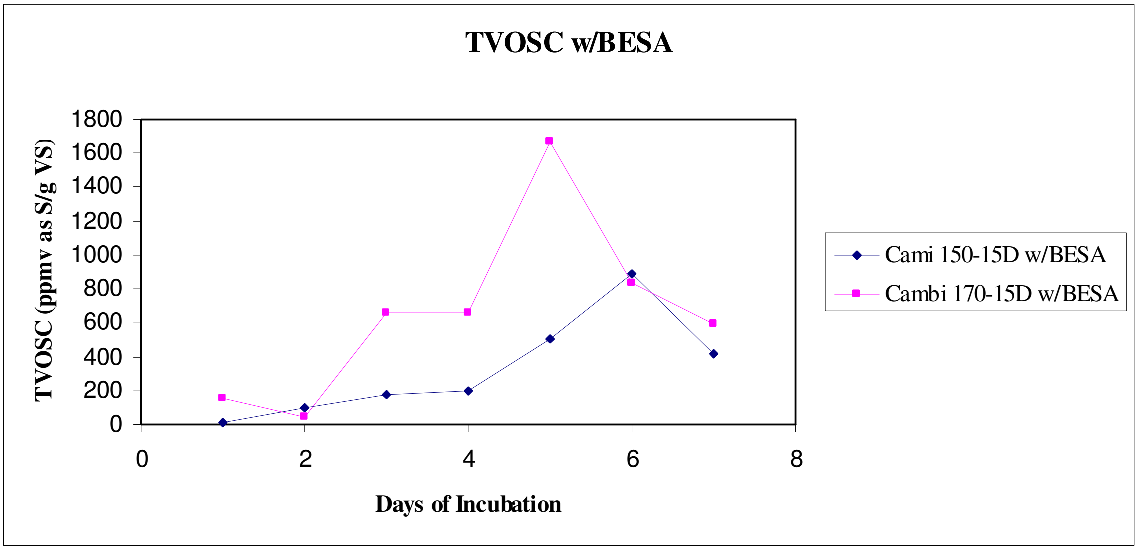


Figure 2-21: TVOSC values for anaerobic digesters, with BESA included.

2.6 Summary

The analysis of results obtained from this study suggests that the anaerobic digestion with Cambi pre-treatment provides several advantages over conventional anaerobic digestion. For the initial phases the VSR and COD reduction were lower compared to later phases. This was mainly because lower period of operation. Anaerobic digestion with Cambi pretreatment took about 400 days to get acclimated and then the results of several analyses were more consistent. Anaerobic digestion at 15 day SRT and 20 day SRT with Cambi pretreated temperature 150^{o}C helped in achieving higher volatile solids reduction, COD reduction and higher biogas production. However, the Cambi pretreatment greatly increased the ammonia production and this is mainly because of higher solids anaerobic digestion. Efforts were made to reduce this ammonia by operating an aerobic digester downstream to the anaerobic digester. Cambi pre-treatment greatly reduced odors because of the process mechanism when compared to conventional anaerobic digestion.

2.7 Conclusions

This research was conducted to study the advantages and disadvantages of the Cambi process as pretreatment for anaerobic digestion. Various characteristics were measured to assess the performance of the Cambi and Control (Non-Cambi) systems. Different parameters, such as COD removal, VS destruction, biogas production, Nitrogen removal and odor removal were studied and the results were compared among different processes. The following conclusions were drawn from the study.

1. **There was little difference in the performance between Cambi MAD-37-15D and Cambi MAD-42-15D**

These results suggested that the process can be operated at any mesophilic temperature range without altering VS or COD removal. However the higher temperature range (42^{o}C) gave higher effluent ammonia concentrations than lower temperature range (37^{o}C). The difference was about 600 mg/L.

2. **Cambi THP-150-15D performed slightly better than Cambi THP-170-15D**

Cambi THP-150-15D and Cambi THP-170-15D were both operated at 15 day SRT, Cambi THP-150-15D gave comparable performance compared to Cambi THP-170-15D in almost all the aspects of interest such as VS reduction, COD removal, biogas production. Operation at 150^{o}C is suggested for the full-scale plant because it will reduce costs.

3. **Cambi THP-150-20D performed slightly better than Cambi THP-150-15D**

Cambi THP-150-20D gave slightly higher VS reduction, COD reduction and Biogas production than cambi THP-150. The difference between both of these digesters was SRT: one was maintained at 20 days SRT and the other was maintained at 15 days. The reason for lower ammonia concentrations in Cambi THP-150-20D was because of ammonia stripping.

4. **Cambi process as a pretreatment to anaerobic digestion resulted in higher cake solids concentration ~36-38% and lower odors compared to conventional anaerobic digestion**

Cambi process as pretreatment to anaerobic digestion gave higher cake solids concentration, which is always advantageous for land disposal. Lower odors are always beneficial for human health and environmental factors.

References

APHA, AWWA, and WPCF. Standard Methods for the Examination of Water and Wastewater, 20th Ed.; Washington, D.C. 1998.

Banjade, Sarita. Anaerobic/Aerobic Digestion for Enhanced Solids and Nitrogen Removal. *Master's Thesis, Virginia Polytechnic Institute and State University, 2008.*

Bougrier, C., Delgenès, J.-P., and Carrère, H. Combination of Thermal Treatments and Anaerobic Digestion to Reduce Sewage Sludge Quantity and Improve Biogas Yield. *Process Safety and Environmental Protection, 84(B4): 280-284, 2006.*

Camacho, P., Ewert, W., Kopp, J., Panter, K., Perez-Elvira, S. I., Piat, E. Combined experiences of thermal hydrolysis and anaerobic digestion – latest thinking on thermal hydrolysis of secondary sludge only for optimum dewatering and digestion. *Water Environment Federation, WEFTEC 2008.*

Chauzy, J., Graja, S., Gerardin, F., Crétenot, D., Patria, L., and Fernandes, P.. Minimization of excess sludge production in a WWTP by coupling thermal hydrolysis and rapid anaerobic digestion. *Water Science & Technology Vol. 52, No.10-11, pp. 255-263, 2005.*

Cheol Cha, Gi., and Noike, Tatsuya. Effect of Rapid Temperature Change and HRT on Anaerobic Acidogenesis. *Wat. Sci. Tech. Vol. 36, No. 6-7, pp. 247-253, 1997.*

Cohen, A., Breure, A. M., van Andel, J. G., and A. van Deursen. Influence of Phase Separation on the Anaerobic Digestion of Glucose-II. *Water Res. Vol. 16, pp. 449-455, 1982.*

De Michele, E. In The National Biosolids Partnership: Background, Progress and the Future. *Proceedings of Biosolids Management in the 21st Century, College Park, Maryland, 2000.*

Fjaergard, T., Sorensen, G., Solheim, O. E., and Seyffarth, T. Cambi Thermal Hydrolysis Combined with Thermophilic/mesophilic Digestion- From Pilot to Full Scale Application at Hamar WWTP. *Proceedings from 11th European Biosolids and Organic Resources Conference, Wakefield, UK, 2006.*

Frechen, Franz-Bernd., and Köster, Wulf. Odour Emission Capacity of Wastewaters-Standardization of Measurement Method and Application. *Wat. Sci. Tech. Vol. 38, No. 3, pp. 61-69, 1998.*

Glindemann D, Murthy SN, Higgins MJ, Chen YC and Novak JT. Biosolids incubation method for odorous gas measurement from dewatered sludge cakes. *Journal of Residuals Science & Technology 3(3), 153-160, 2006.*

Gonzalez-Fernandez. Cristina, Garcia-Encina A. Pedro. Impact of substrate to inoculums ratio in anaerobic digestion of swine slurry. *Biomass and Bioenergy, 33, 1065- 1069, 2009.*

Grady, C.P. Leslie, Daigger, Glen T., Lim, H.C., Biological Wastewater Treatment, *Marcel Dekker, New York, 1999.*

Hariklia N. Gavala, Umur Yenal, Ioannis V. Skiadas, Peter Westermann, and Birgitte K. Ahring. Mesophilic and thermophilic anaerobic digestion of primary and secondary sludge-effect of pre-treatment at elevated temperature. *Water Research 37, 4561-4572, 2003.*

Higgins, Matthew J., Chen, Yen-Chih., Yarosz, Douglas P., Murthy, Sudhir N., Maas, Nick A., Glindermann, Dietmar., and Novak, John T. Cycling of Volatile Organic Sulfur Compounds in Anaerobically Digested Biosolids and its Implications for Odors. *Water Environment Research, Volume 78, Number 3, 243-252, 2006.*

Jolis, Domènec. High-Solids Anaerobic Digestion of Municipal Sludge Pretreated by Thermal Hydrolysis. *Water Environment Research, Volume 80, Number 7, pp. 654-662, 2008.*

Kepp, U., Machenbach, I., Weisz, N., and Solheim, O. E. Enhanced stabilization of sewage through thermal hydrolysis-three years of experience with full scale plant. *Water Science and Technology, Vol. 42, No. 9, pp. 89-96, 2000.*

Leitao, Renato Carrhá; van Haandel, Adrianus Cornelius; Zeeman, Grietje; and Lettinga, Gatze. The effects of operational and environmental variations on anaerobic wastewater treatment systems: A review. *Bioresource Technology 97, 1105-1118. 2006.*

Kim, H., Murthy, S., McConnell, L. L., Peot, C., Ramirez, M., and Strawn, M. Characterization of wastewater and solids odors using solid phase microextraction at a large wastewater treatment plant. *Water Science and Technology Vol. 46, No. 10, pp. 9-16, 2002.*

McCarty, Perry L., and Smith, Daniel P. Anaerobic Wastewater treatment. *Environ. Sci. Technol., Vol. 20, No. 12, 1986.*

Müller, J. A. Prospects and problems of sludge pre-treatment processes. *Water Science and Technology, Vol. 44, No. 10, pp 121-128. 2001.*

Murthy, S. N., Forbes, B., Burrowes, P., Esqueda, T., Glindemann, D., Novak, J., Higgins, M. J., Mendenhall, T., Toffey, W., Peot, C. Impact of High Shear Solids Processing on Odor Production from Anaerobically Digested Biosolids. *Proceedings of the 75th Annual Water Environment Federation Technical Exposition and Conference, Chicago, Illinois, Water Environment Federation, Alexandria, Virginia, 2002.*

Neyens, E., and Baeyens, J. A review of thermal sludge pre-treatment processes to improve dewaterability. *Journal of Hazardous Materials B98, 51 – 67, 2003.*

Novak, John T. Dewatering of Sewage Sludge. *Drying Technology, 24: 1257-1262, 2006.*

Pickworth, B., Adams, J., Panter, K., and Solheim, O. E. Maximizing biogas in anaerobic digestion by using engine heat for thermal hydrolysis pre-treatment of sludge. *Water Science & Technology Vol. 54, No. 5, pp. 101-108, 2006.*

Rittman, B.E., McCarty, P.L. Environmental Biotechnology: Principles and Applications. *McGraw-Hill, Boston, 2001.*

Spinosa, L., and Vesilind P. Aarne. Sludge into Biosolids: Processing, Disposal and Utilization. *IWA Publishing, Alliance House, 12 Caxton Street,London SW1H0QS, UK, 2001.*

Tchobanoglous, G., Burton, F.L., Stensel, H.D. Wastewater Engineering: Treatment and Reuse. *Metcalf & Eddy Inc., 4th Ed., McGraw-Hill, New York, 2003.*

Van Leerdam, Robin C., De Bok, Frank A. M., Lomans, Bart P., Stams, Alfons J. M., Lens, Piet N. L., and Janssen, Albert J. H. Volatile Organic Sulfur Compounds in Anaerobic Sludge and Sediments: Biodegradation and Toxicity. *Environmental Toxicity and Chemistry, Vol. 25, No. 12, pp. 3101-3109, 2006.*

Wilson Christopher. A., Murthy, Sudhir N., Novak John T. Novak. Laboratory-Scaled Digestibility Study of Wastewater Sludge Treated by Thermal Hydrolysis. *Residuals and Biosolids, 374-386, 2008.*

Zhang, Tian C., and Noike, T. Influence of Retention Time on Reactor Performance and Bacterial Trophic Populations in Anaerobic Digestion Processes. *Wat. Res. Vol. 28, No. 1, pp. 27-36, 1994*.

3 COMBINED ANAEROBIC/AEROBIC DIGESTION OF THERMALLY HYDROLYZED SLUDGE

ABSTRACT

The study deals with aerobic digestion of anaerobically digested sludge for effective nitrogen removal and additional VS destruction, COD removal. An aerobic digester is operated downstream to anaerobic digester and is operated with aerobic/anoxic phase for nitrification and de-nitrification. The aerobic/anoxic phases are operated in time cycles which included 40minutes/20minutes, 20 minutes /20 minutes, full aeration, 10 minutes /30 minutes, and 12 minutes /12 minutes. Different time cycles are experimented and aerobic digester is optimized for effective nitrogen removal. 12minutes aerobic and 12 minutes anoxic phase gave better nitrogen removal compared to all the cycles. Over all the aerobic digester gave about 92% ammonia removal, 70% VS destruction and 70% COD removal.

The oxygen uptake rates (OUR's) in the aerobic digester are measured corresponding to maximum nitrogen removal. The OUR's are found to be close to 60 mg/L. Dissolved oxygen also played very important role in nitrogen removal, the optimum DO was found to be 4mg/L in aerobic phase and 0.5 mg/L in anoxic phase.

The effluent from both anaerobic digester and aerobic digester was collected and analyzed for dewatering capability, cake solids concentration and odor potential. Anaerobically digested sludge gave higher cake solids concentration at about 40% total

solids and lower odors compared to aerobic digester On the other hand, aerobically digested sludge had higher polymer dose. The cake solids concentration for the aerobic digester was 32%.

3.1 Introduction

Sludge digestion is a biological process in which organic solids are decomposed into stable substances. Digestion reduces the total mass of solids, destroys pathogens, and makes it easier to dewater or dry the sludge (Grady *et al.,* 1999). Anaerobic digestion results in accumulation of soluble ammonia while degrading organic matter.

Lab-scale investigation showed that the stabilization of anaerobically digested sludge increases with post-aerobic digestion (Parravicini *et al.,* 2006). A digester operated with an aerobic phase and an anoxic phase has many advantages over the aerobic digestion alone. Alternating aerobic/anoxic provides alkalinity recovery, energy saving and nitrogen removal (Al-Ghusian *et al.,* 1995).

In aerobic digestion sewage sludge is bio-chemically oxidized by bacteria. Generally the aerobic micro-organisms are supplied with oxygen by vigorous mixing or forcibly injecting air or oxygen (U.S. EPA, 2003). The solids are oxidized with oxygen or nitrate-N as the terminal electron acceptor (Grady *et al.,* 1999). Aerobic digestion produces sludge suitable for disposal from small scale WWTP's because it produces a more stable sludge, free from nuisance odors and is of low cost (Matsuda *et al.,* 1988).

As the aerobic digestion process releases nutrients, the nitrogen cycle plays very important role. In domestic waste waters, most of the nitrogen is in the form of ammonia (NH_3) and organic nitrogen. In some aerobic digesters, combined aerobic and anoxic operation will lead to denitrification in which inorganic nitrogen is converted to nitrogen gas (N_2) (Grady *et al.,* 1999).

Aerobic digestion is affected by various factors which includes pH, temperature, solids retention time, concentration of sludge, mixing, oxygen uptake rate (OUR) and type of operation (full aeration or aerobic/anoxic) (Ganczarczyk *et al.,* 1980, Matsuda *et al.,* 1988, Khalili *et al.,* 2000, Warner *et al.,* 1986, Huang *et al.,* 1985, Grady *et al.,* 1999). The SRT exerts a very dominant effect in the performance of the biochemical operations. If the SRT is maintained too low biodegradable organic matter will be washed out from the reactor. Tyagi *et al.,* (1990) studied mesophilic and thermophilic aerobic digestion for municipal sludge and showed that nitrification is inhibited temperatures exceeding 40^{o}C.

Nitrogen removal has long been established and is possible by nitrification followed by denitrification. However the major challenge is to identify the conditions for the two phenomena to coexist, because of their contrasting requirements (Tchobanoglous *et al.,* 2003, Li *et al.,* 2008). The challenge is to create a balance or a cycle where the aerobic and anoxic conditions occur without interfering with each other. This can potentially be achieved by controlling the oxygen supply in a timely manner, i.e. by maintaining alternating aerobic and anoxic phases. Oxygen is supplied during the aerobic phase and turned off for the anoxic phase (Grady *et al.,* 1999).

Post aerobic treatment of anaerobically digested sludge has several advantages; the organic solids can be reduced further by up to 20% and enhanced nitrogen removal can occur by intermittent aeration through nitrification and denitrification (Parravicini *et al.,* 2008). Akunna *et al.,* 1994 showed that the amount of ammonia nitrogen to be nitrified depends on the amount of organic matter in the digested effluent. He was able to achieve 70% ammonia removal and 60% COD removal for anaerobic digestion and post aeration treatment. Kumar (2006) studied combined aerobic and post aerobic digestion with different SRT's. He found better ammonia removal as the SRT is increased; overall ammonia removal increased to greater than 80%. Banjade (2008) studied sequential anaerobic and aerobic digestion and achieved around 62% VS reduction, 70% COD reduction, Compared to 50% by anaerobic digestion alone.

3.2 Research Objectives

Many researchers have been successful in performing aerobic digestion with full aeration or with an aerobic/anoxic phase and also with aerobic digestion as post treatment to anaerobic digestion. But after a review of literature, no references could be found for systems with thermal hydrolysis as pretreatment to anaerobic digestion and aerobic digestion as post treatment to anaerobic digestion with an aerobic/anoxic phase. The main purpose of this study was to study combined anaerobic-aerobic digestion using thermally pretreated sludge. Pretreatment was attained by using the Cambi process.

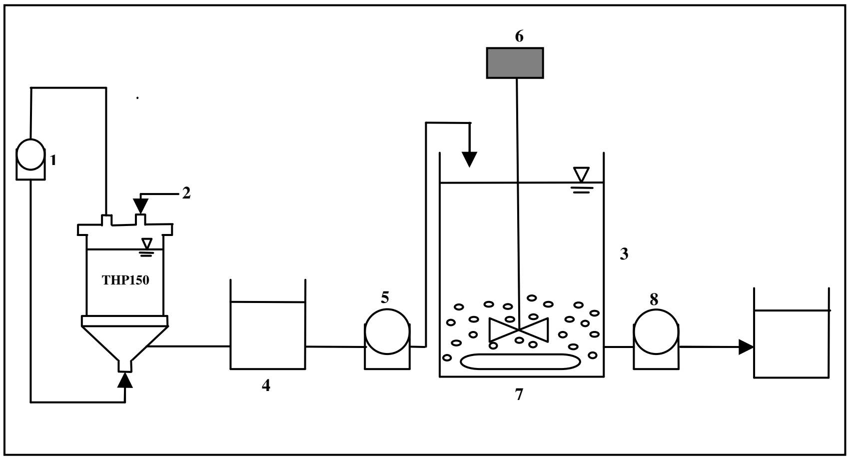
The main objectives of the study were:

1. To optimize removal of nitrogen by nitrification/denitrification in post aerobic digestion.

2. To determine degree of additional removal of COD and VS from the anaerobic digester.
3. To evaluate the potential for odor reduction using combined Cambi anaerobic/aerobic digestion.
4. To determine the mass of oxygen supply occurring during the removal of nitrogen species.

3.3 <u>Methodology</u>

The schematic of the aerobic sludge digestion process with Cambi anaerobic digester is shown in figure 3-1.



1: Peristaltic pump.
2: Cambi hydrolyzed feed. ~ 10.0% Total Solids;
3: Aerobic Reactor, Cyclic 6.0L, 6 Day SRT.
4: Influent for aerobic reactor
5: Feed pump to aerobic reactor.
6: Paddle Mixer (200 RPM). Operated during anoxic cycle
7: Bubble diffuser which operates during aerobic cycle.
8: Wastage pump from aerobic reactor.

Figure 3-1: Schematic of aerobic sludge digestion process with Cambi anaerobic digester.

This study deals with aerobic digestion using various time cycles for the aerobic/anoxic phase to optimize nitrogen removal. One aerobic and one anaerobic digester were set up, both operated as continuously stirred tank reactors (CSTRs). The aerobic digester was maintained at 37°C (temperature was decreased due to air addition, the temperature inside the aerobic digester was 34^{o}C) mesophilic temperature (Cambi AER) with a 6 days SRT. The anaerobic digester was also maintained at 37°C and 15 days SRT. Cambi pretreated sludge was the feed to the anaerobic digester (Cambi THP-150-15D) and its effluent was the feed to the aerobic digester. Results for the anaerobic digestion may be found in Tanneru *et al.,* 2009. The active volume of the aerobic digester was 6 L. To maintain a constant SRT, 1 L of the sludge was taken out and 1 L of the feed was fed to the digester each day. The effluent was taken out at the end of an aerobic phase and the feed was given at the beginning of an anoxic phase.

The feeding and effluent removal operation was programmed to feed or extract 28 mL of sludge every 40 minutes. Feed and effluent pumps achieve this function using 36 cycles per day. The time that effluent pump or the feed pump ran was calculated by conducting several trials. The effluent pump ran for 7 seconds to flush 28 mL from the digester and the feed pump ran for 4 seconds to pump 28 mL in to the digester. The feed is provided at the beginning of anoxic cycle because it is considered that the organic matter serves as carbon source during denitrification and the effluent was drawn at the end of the aerobic stage.

The digester was operated with aerobic and an anoxic phase. The aerobic phase occurs during aeration and the anoxic phase was when the air turns off and paddle mixer turns on. This was achieved by a ChronTrol. ChronTrol is a device which can balance four different circuits and the time interval can be set for each circuit. A ChronTrol which has 4 circuits was used for this study for maintaining proper time intervals. The first circuit was connected to an air pump. The second circuit was connected to the effluent pump, the third circuit was connected to a paddle mixer and the fourth circuit was connected to feed pump.

Two types of aerobic digesters were used throughout the study. The first digester (Cambi AER 1) was a plastic nalgene container with an open lid at the top and 10 L capacity. Holes were made in the bottom of the container and plastic tubes were inserted for the air supply. The inlets were tightly sealed to ensure that sludge did not leak from the bottom. An air pressure pump was used for the air supply. A paddle mixer was used for mixing and the mixer was connected to a motor which rotated at 200 rpm. This paddle mixer was mounted to the container from the top. Two tubes were inserted into the digester, one for feed and one for effluent. The maximum dissolved oxygen (DO) obtained in this digester was 1- 1.5 mg/L.

To improve the performance of the aerobic digester and to increase the DO concentration, the reactor system was changed. The second digester (Cambi AER 2) was a glass container with 15 L capacity. The glass container had a solid metal top and the top has various connections which included a mixer with blades. The mixer had holes through which air was supplied. The lid has provisions for adding feed and removing effluent. The oxygen was supplied from gas cylinders. Two types of cylinders were used, one with breathing air and the other with 50% oxygen and 50% nitrogen. The gas was supplied to the digester by connecting tubes from the cylinder to the digester. The pressure maintained in these tubes was approximately 150 psi. The flow of oxygen into the digester was controlled using a rotameter (Cole Parmer range 1-5 cubic foot per hour) attached between these tubes. The tubes were capable of withstanding pressures up to 300 psi. The dissolved oxygen inside the digester was monitored continuously by placing a DO probe inside the digester. Initially LDO probe was used for this study. Later, a membrane probe was also used. The dissolved oxygen in the digester was maintained at approximately 4mg/L during the aerobic phase. In the anoxic phase the oxygen was stopped by placing a solenoid valve between the gas cylinder and the digester. This restricts the oxygen from flowing in to the digester during the anoxic phase. A ChronTrol is used for balancing the circuit. The first circuit was connected to the effluent pump, the second one was connected to solenoid circuit and the third one was connected to the influent pump. The mixer remained on in both phases. Carbon dioxide was supplied to the digester continuously to maintain a constant pH and also to counter CO_2 that was stripped from the digester.

Table 3-1 shows the various digesters operated during the study and it also shows their SRT's, operating temperature and period of operation.

Table 3-1: Acronyms for aerobic and anaerobic digesters used during results and discussion and operational characteristics.

Digester Acronym	SRT (Days)	Operating Temperature (°C)	Number of Days of Operation
Cambi THP-150-15D	15	37	1 year 3 months
Cambi-AER	06	37	9 months
Control-MAD	20	37	18 months

3.4 Analytical Methods

The analyses like pH, COD, total solids, volatile solids, Total Kjeldahl Nitrogen (TKN), ammonia were measured according to Standard Methods for the examination of Water and Waste Water (APHA 1998). Volatile fatty acids (VFA's) were determined as follows, the samples of sludge were centrifuged in Beckman-Coulter Avanti-JE centrifuge at 10000 RPM for 30 min and then supernatant filtered through a 0.45µm filter (nitrocellulose disc filters, Fischer Scientific). The filtered samples were acidified with 85% phosphoric acid before measurement. VFA's were measured using a Shimadzu GC-14A Gas Chromatograph with a Nukol Column and Flame ionization detector. Helium was used as the carrier gas at a flow rate of approximately 17 ml/min. Other gas flow rates were nitrogen- 13 ml/min, hydrogen-45 ml/min, air- 450 ml/min. A Shimadzu computer integrator CR501 chromatopak was used for data analysis. VFA's measured were acetic acid, propionic acid, butyric acid, isobutyric acid, valeric acid, isovaleric acid, heptanoic acid and caprionic acid.

CST, Optimum Polymer Dose and Odor

Generally anaerobic digestion is used to process sludge for land application, but research has shown that anaerobic digestion and dewatered biosolids cakes can generate unacceptable odors (Murthy *et al.,* 2002). The odor generation from the dewatered cake after anaerobic digestion was studied in the lab by using the method of Glindemann *et al* (2006), which is described in more detail below.

One hundred mL of sludge was collected and cationic polymer (WLSSD polymer 1% w/w) was added and sheared in wearing blender for 30 seconds. The time to dewater this sample is recorded on CST apparatus (Triton 165, Triton 304-M). The process is repeated until the lowest CST is obtained. This CST is considered to be the optimum polymer dose.

After the CST was determined, 400mL of sample was collected and conditioned with the cationic polymer dose which was found from the CST testing. The sludge was then centrifuged in Beckman-Coulter Avanti-JE centrifuge at 10000 RPM for 30 min at 4^{o}C. The pellet was collected and further dewatered using hydraulic piston press. The pellet was placed on Whatman 41 filter paper and pressed at a pressure of 39 psi for 15 minutes. The sludge cake obtained is broken in to small pieces. Five grams of cake was weighed and placed in a bottle. Triplicates of samples are prepared. The bottles were then sealed with screw cap and Teflon-lined septa to prevent the loss of gas. The bottles were incubated over a period of 3 weeks at a constant room temperature. The samples with bromo ethane sulfonic acid (BESA) were also analyzed for methanogenisis inhibition. BESA (0.127 mM) was added to the odor bottle (1-2 mL) before capping. The cake total solids and volatile solids were measured to determine cake solid concentration as in Standard Methods for the examination of Water and Waste Water (APHA 1998).

Odor Analyses

The cake inside bottle was expected to produce VOSC's in the head space and so it was analyzed for VOSC's (MT, DMS, DMDS) and H_2S using gas chromatography/mass spectrometry (GC 5890, MSD 5970) with Supelco Equity-5 column and 30m x 0.25 mm capillary column of film thickness 1 µm. 25 µL of gas was collected from the syringe and inserted in to the inlet column. Liquid nitrogen was used as trap to obtain narrow peaks and for maximum separation of compounds.

Oxygen Uptake Rates (OUR)

Oxygen uptake rates were measured very carefully throughout this study. The oxygen uptake rates were measured from the dissolved oxygen data obtained from Lab View 7.1 software and a computer connected to the circuit. A code was developed for this purpose which facilitates recording of DO values every 10 seconds. The LDO probe that was in the digester was connected to the computer and this probe facilitates to record the values and thus OUR's can be measured in-situ at any point of time. The program was developed in Lab View 7.1 works in such a way that the maximum and minimum DO limits can be set. The maximum DO was 4 mg/L and minimum DO was 0.5 mg/L. The program always tries to operate in the range of 4 mg/L to 0.5 mg/L, whenever the DO becomes greater than 4 mg/L, the solenoid valve closes and the air flow stops and when the DO is less than 0.5 mg/L the solenoid valve turns on and the air flows into the digester. The oxygen uptake rates were calculated from these recorded values.

The OURs were also measured ex-situ of the digester. An YSI membrane probe was used for this study. A sample of 100 mL was collected and the YSI probe was immersed in the sample. The rate of oxygen depletion was measured for this sample.

Nitrite and Nitrate analyses

Nitrite analysis was performed using HACH tubes. This is called the test and tube method. HACH TNT-840 tubes were used for this test. 0.2 ml of sample was injected into the tube and mixed with the reagent given. After 10 minutes pink color develops if the nitrite is present. The nitrite concentration was found from Spectrophotometer by plotting a standard curve with absorbance and concentration. Nitrite was also measured using a similar method.

3.5 Results and Discussion

The effluent from anaerobic digester was used as the feed to aerobic digester. The anaerobic digester was operated with thermal hydrolysis (Cambi) pretreated sludge (Tanneru *et al.,* 2009). All the analyses were performed after achieving steady state conditions in the digesters. Steady state was determined by daily monitoring. When little variation occurred in parameters such as pH, VS removal and COD reduction steady state was assumed. Various analyses performed include pH, total and volatile solids reduction, COD removal, TKN and ammonia removal, presence of nitrite and nitrate in aerobic digester, and VFA's production and destruction.

The average values for measured parameters VS removal, COD removal for each phase at steady state are shown in figures 3-2 and 3-3 respectively. VS removal for the control-MAD was obtained from Banjade (2008) and VS removal for the Cambi THP-150-15D was obtained from Tanneru *et al.,* (2009).

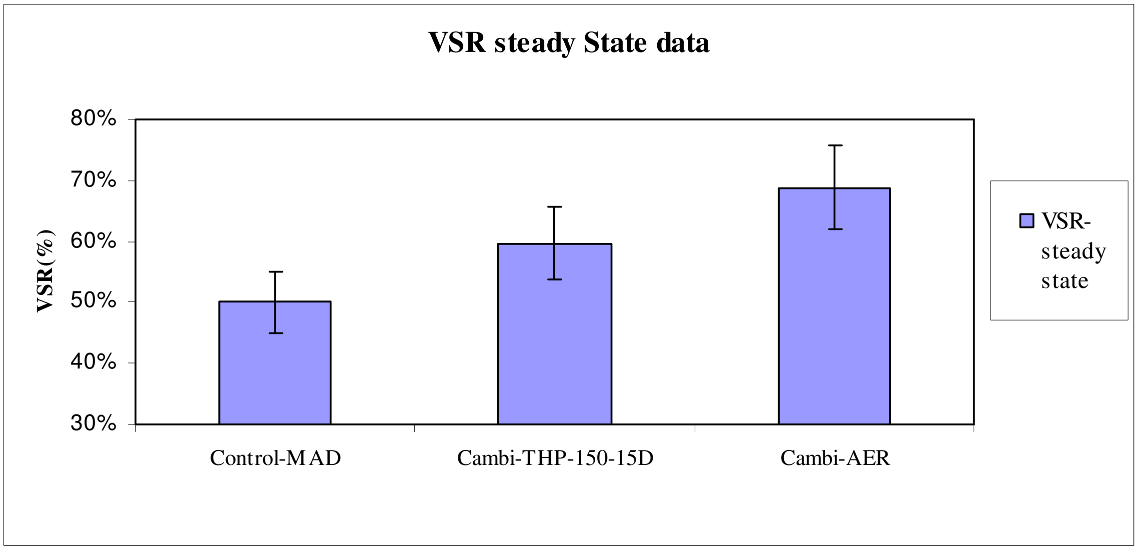


Figure 3-2: VSR values during steady state.

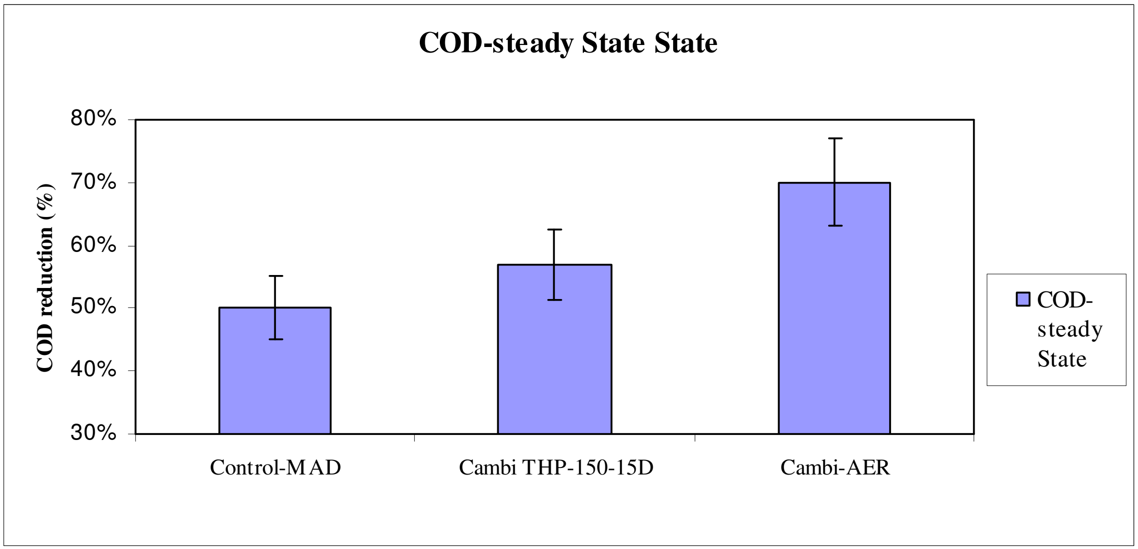


Figure 3-3: COD values during steady state.

In figures 3-2 and 3-3 it can be seen that the VS removal and COD reduction increased from Control-MAD to Cambi THP-150-15D (Tanneru *et al.*, 2009) and most importantly post aerobic digestion resulted in additional VS removal and COD reduction.

Co-relation between VS and COD

Biodegradability is generally expressed as a percentage of either COD removal or VS reduction. These characteristics change depending on the feed concentration. COD can be correlated with the VS of the sample, the relation being empirical. This ratio varies from sample to sample, For carbohydrates it is around 1.1, for lipids it is 2.9, for protein it is 1.5 (Spinosa *et al.,* 2001). This correlation is called as substrate/inoculum ratio.

Figure 3-4 shows the correlation between VS and COD from Cambi THP-150-15D and Cambi-AER. The aerobic digester had less variability of both, this is mostly because the anaerobic digester feed concentrations that had been shipped from Blue Plains waste water treatment plant varied consistently. Table 3-2 shows the COD/VS ratio for anaerobic and digesters. Ratios vary considerably from process to process and these ratios suggest that the anaerobic digestion and following aerobic digestion with Cambi pretreated sludge operated successfully at these COD/VS ratio.

Table 3-2: COD/VS ratios for different digesters.

Type	COD/VS
Cambi THP- 150-15D	2.28
Cambi AER	1.74
Control MAD	1.38

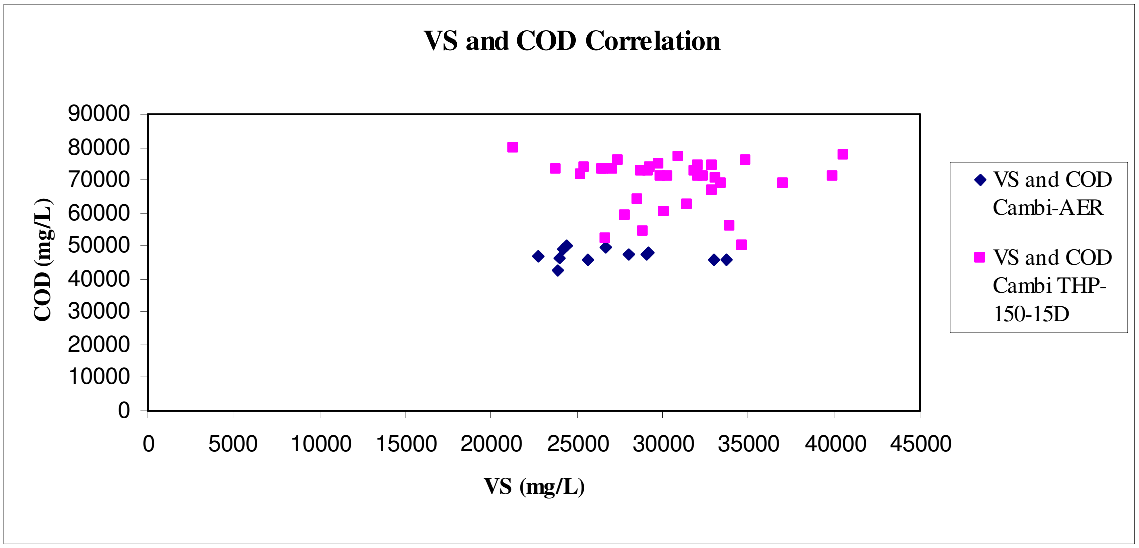


Figure 3-4: VS and COD correlation in Cambi THP-150-15D and Cambi AER.

The COD/VS ratio decreased in aerobic digester compared to the anaerobic digester, this shows the more stabilized and controlled performance of the digester. However, the higher ratio in the anaerobic digester is mostly because of higher proteins and lipids in the anaerobic digester.

pH

The pH plays an important role in aerobic digestion and is also linked to nitrogen cycle. Variations in pH directly affect the nitrification and denitrification, the changes in ammonia concentration affect the pH. Nitrification consumes alkalinity and decreases pH. Denitrification converts all ammonia to nitrogen gas. When nitrification and denitrification occurs simultaneously the pH will be balanced somewhat by both the phases (Grady *et al.,* 1999). The minimum pH was 6 and the maximum was found to be 8 for best aerobic and anoxic operation (Al-Ghusian *et al.,* 1995).

The pH of aerobic digester was 7.41±0.70 ($x \pm \mu$). The pH data is shown in the figure 3-5. Initially the pH was very high up to 8.5. This was considered to occur due to CO_2 stripping from the aerobic digester during aeration and would not be expected to occur in a full-scale system with a greater liquid depth. To counteract this stripping, CO_2 was bubbled in to the digester. This brought down the pH to 7.4. During the full aeration phase, nitrite built up in the aerobic digester during nitrification in the form of nitrous acid. This resulted in reduction of pH to 5.8. When denitrification began to occur, the pH was again increased to 7.

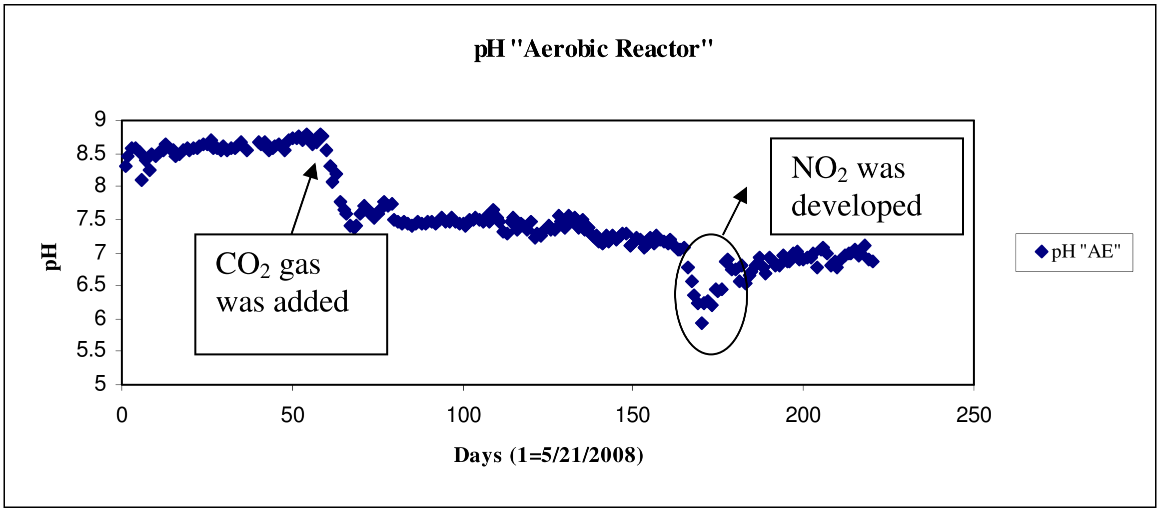


Figure 3-5: pH of the aerobic digester.

Volatile Solids Reduction (VSR)

The advantage of post aerobic digestion for anaerobically treated sludge is additional solids destruction, COD reduction and more stable sludge (Parravicini *et al.,* 2006). This is reflected in figure 3-6. The average overall VS reduction for aerobic digester was 69.18%±1.26%. The average total solids feed concentration to the aerobic digester was 6%. Anaerobic digestion (Cambi THP-150-15D) with Cambi process pretreated sludge gave 58% solids destruction (Tanneru *et al.,* 2009) and conventional anaerobic digestion (Control-MAD) gave 50% solids destruction (Banjade 2008). Post aerobic digester increased solids destruction by 20% compared to conventional anaerobic digestion and post aerobic digester gave 10% additional solids from the anaerobic digester and this is considered to be as very effective.

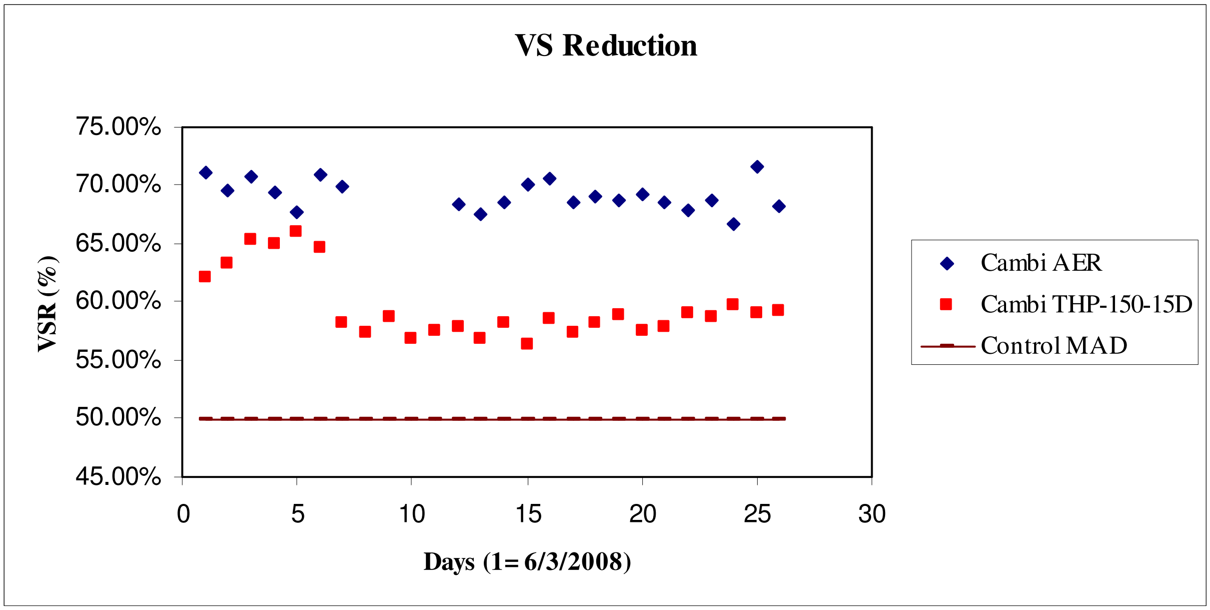


Figure 3-6: Total Volatile Solids reduction for the aerobic digester.

COD reduction

Post aerobic treatment also increases the COD reduction from anaerobically digested sludge. Kumar (2006) conducted sequential anaerobic/aerobic digestion and he got 60-70% overall COD reduction. Banjade (2008) conducted studies on anaerobic and aerobic digestion and measured 70% overall COD reduction. The COD reduction data is shown in the figure 3-7. The average overall COD reduction for aerobic digester was 69.8%±1.90%. Post aerobic digestion resulted in 12-15% higher COD reduction compared to anaerobic digestion with Cambi process pretreated sludge which was 56% (Tanneru *et al.,* 2009). When compared to conventional mesophilic digestion for which COD reduction was 50% (Banjade *et al.,* 2008) post aerobic digestion resulted in 20% additional COD reduction. The variations in COD values were very high because of higher dilutions up to 1:200 and also the changes in feed compositions and concentrations. The soluble COD values are shown in the figure 3-8.

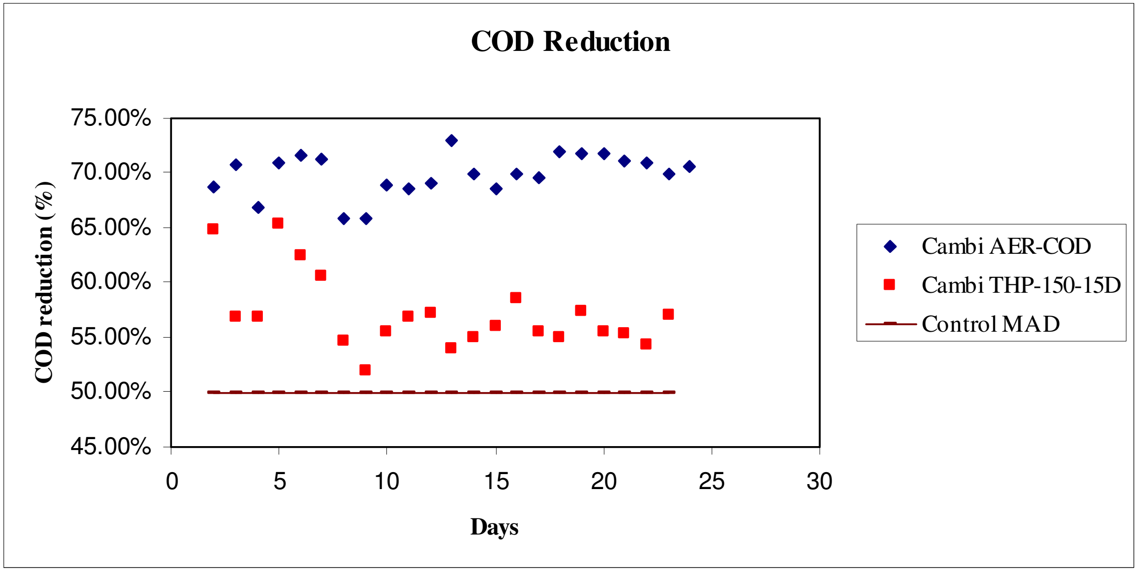


Figure 3-7: Total COD reduction for the aerobic digester.

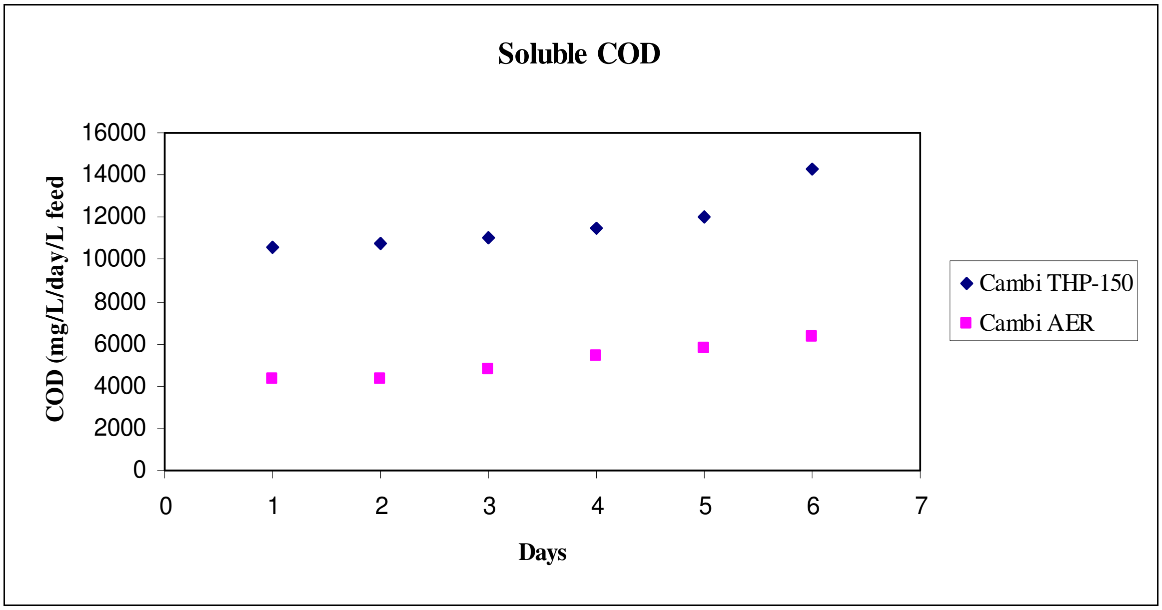


Figure 3-8: Comparison of soluble COD of Cambi anaerobic and aerobic digesters.

The average soluble COD values for Cambi THP-150-15D was 11680 mg/L and Cambi AER was 5174 mg/L. These soluble COD values were measured continuously for a week during the best performance of aerobic digester (good nitrification/denitrification), i.e., at 90% ammonia removal. The soluble COD reduction was 55% from Cambi anaerobic digester (Cambi THP-150-15D) to aerobic digester (Cambi AER). This shows that the maximum COD reduction is obtained in soluble form and the particulate COD is not considerably reduced from post aerobic digestion.

TKN and Ammonia Removal

Nitrogen can be effectively removed by adopting an air on (aerobic phase) and air off (anoxic) sequences in the aerobic digester. Nitrification/denitrification is achieved by cycling between aerobic/anoxic conditions. The time interval for each phase is critical (Batchelor *et al.,* 1983). This was considered while conducting this study. Kumar (2006) studied the combined anaerobic and post-aerobic digestion of sludge with aerobic digestion SRT's at 3, 6 and 9 days. In Kumar's study, he aerated continuously and fed anaerobically digested sludge once per day. This resulted in rapid depletion of DO, followed by a slow increase in DO over the next 6 hours. He measured 80% ammonia removal and 50% TKN removal and the ammonia removal was increased as the SRT increased from 3 days to 9 days. Akunna *et al.,* 1994 showed that the amount of ammonia nitrogen to be nitrified depends on the amount of organic matter in the digested effluent. He was able to achieve 70% ammonia removal.

All the ammonia analyses were performed at steady state. Various aerobic/anoxic time cycles were tried throughout the study. The cycles can be seen in Table 3-3.

Table 3-3: Different cycles operated in aerobic digester during aerobic/anoxic phases.

Comments	Cycles (Minutes/Minutes)
Aerobic/Anoxic	40/20
Aerobic/Anoxic	20/20
CQ	Full aeration
Aerobic/Anoxic	25/15
Aerobic/Anoxic	10/30
Aerobic/Anoxic	6/6 (50% feed Concentration)
Aerobic/Anoxic	9/9 (75% feed Concentration)
Aerobic/Anoxic	12/12 (100% feed Concentration)

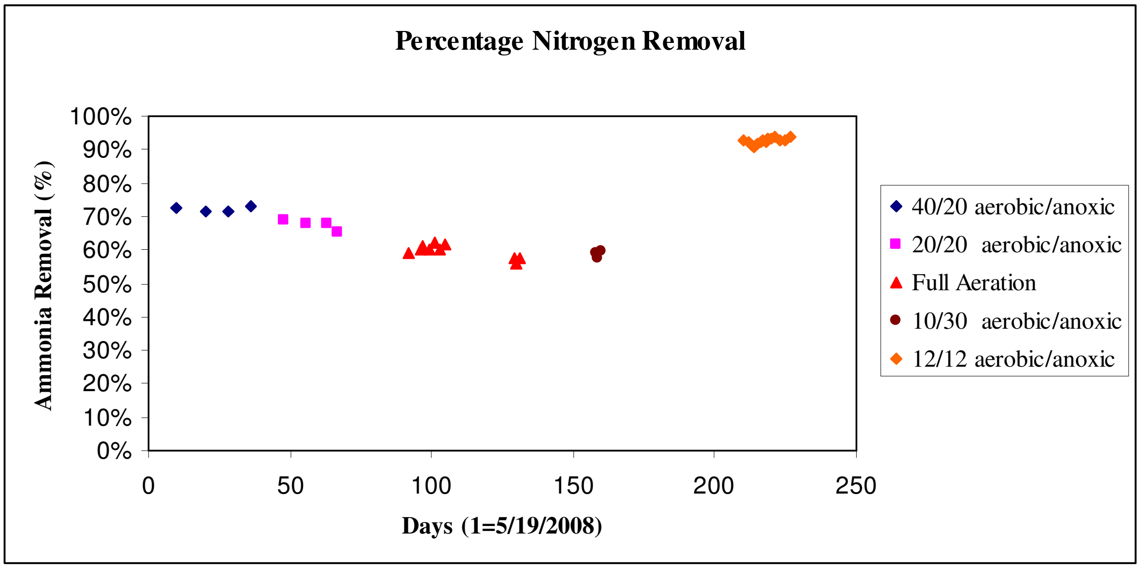


Figure 3-9: Percentage ammonia removal in the aerobic digester for all the phases.

Figure 3-9 shows the ammonia removal in all the phases. The percentage ammonia removal was less for phases 40/20, 20/20, full aeration, 25/15, and 10/30. The average ammonia removal for these phases was ranged from 55% to 72%. The main reason for this is initially for 40/20 and 20/20 phases Cambi-AER 1 is operated and the dissolved oxygen (DO) inside the digester was low (1-1.5 mg/L) and this DO was not considered enough for adequate nitrification.

To achieve better nitrification the aeration should be done effectively. Breathing gas was used for aeration and the aerobic digester was changed to Cambi AER 2. For full aeration, 25/15, 10/30, 6/6 (50% loading), 9/9 (75% loading), 12/12 (100% loading) Cambi AER-2 operation was used. The main problem with this digester was DO is not controlled inside the digester. To increase the ammonia removal an aerobic digester with 3 day SRT was introduced downstream to the aerobic digester but the result was not very commendable. It gave additional 1% solids destruction and overall ammonia removal was only 70%.

For efficient DO control solenoid valves, an LDO probe and Lab View 7.1 software with pre-developed program was used. This resulted in better nitrification and denitrification by controlling the aerobic and anoxic phases efficiently. It was during this period that the ammonia removal increased to greater than 90%. To achieve better ammonia removal various experiments were performed, Initially the loading was reduced to 50% and the time cycles were changed to shorter time intervals (6/6, 9/9,12/12). This was successful and the ammonia gradually reduced from 2500 mg/L to less than 260 mg/L. The loading was then increased to 75%, which was also successful. Finally the loading was increased to 100 % and the time cycle was changed to 12 minutes on/12 minutes off and this resulted in 92% overall ammonia removal. This phase was considered as optimized phase of the aerobic digester because the ammonia removal was highest. Table 3-4 shows overall average ammonia concentrations in mg/L/day and the figures 3-10 show the overall ammonia data and figure 3-11 shows the TKN values for Cambi THP-150-15D and Cambi- AER.

Table 3-4: Average ammonia values and corresponding date ranges for each phase of operation.

	Cycles	**Ammonia (mg/L/day/L feed)**	**SRT (Days)**	**Dates Range**	**Comments**
Aerobic/Anoxic	40/20	721	6	5/21/2008-7/4/2008	
	20/20	828	6	7/4/2008-7/25/2008	pH~8.5
with pH Control	20/20	772	6	7/25/2008-9/5/2008	pH~7.5
	Full Aeration	930	6	9/5/2008-11/10/2008	High Ammonia
	Additional Aerobic	811	(6+3)	11/1/2008-11/25/2008	
	25/15	964	6	11/10/2008-11/20/2008	Short Period
	10/30	838	12	11/25/2008-1/10/2009	
	6/6	267	6	1/11/2009-2/14/2009	50% Loading
	9/9	116	6	2/15/2009-2/24/2009	75% Loading
	12/12	**171**	6	2/25/2009-4/15/2009	Maximum removal-100% Loading

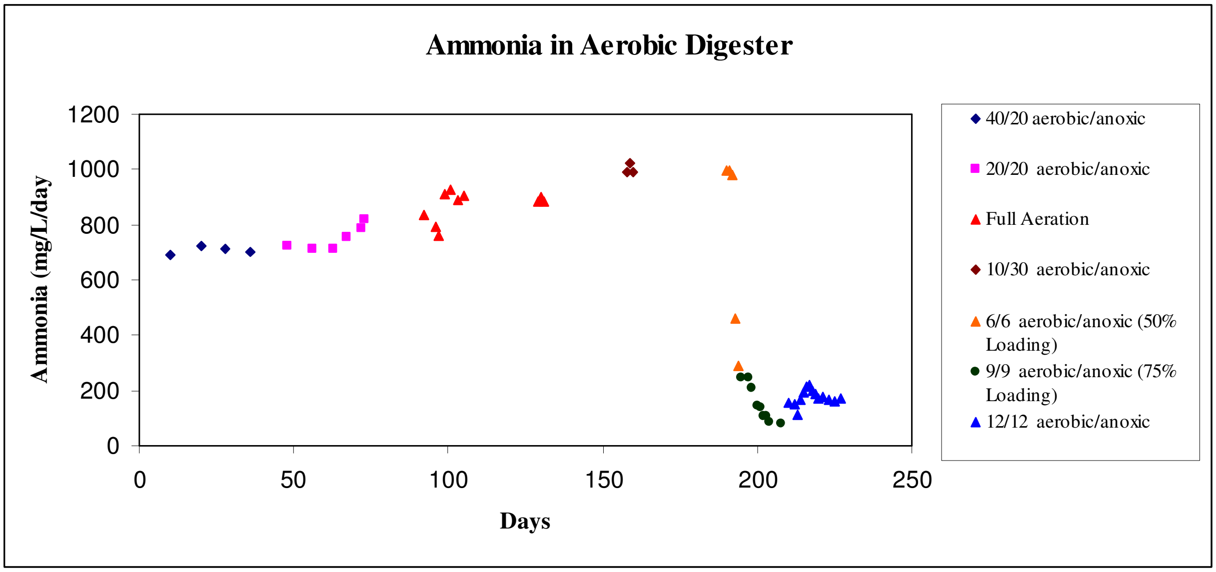


Figure 3-10: Ammonia concentration in the aerobic digester for all the phases.

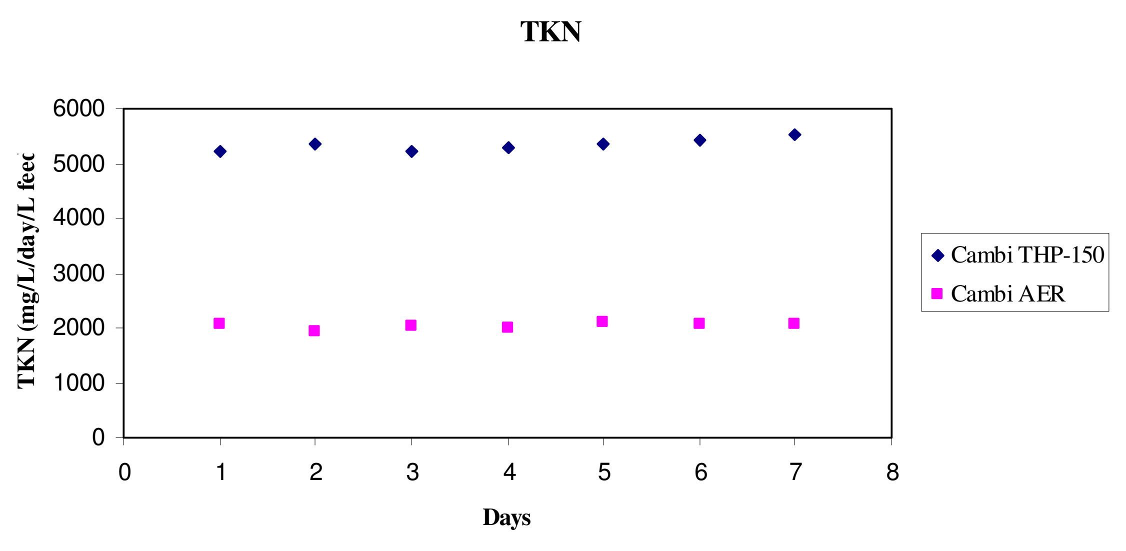


Figure 3-11: Comparison of TKN values of Cambi anaerobic and aerobic digesters.

The average TKN removal was from Cambi THP-150-15D to Cambi AER was 60%. These TKN values were measured at the optimized phase of aerobic digester and the TKN values were measured daily. The results show that the post aerobic digestion resulted in good TKN removal, the organic nitrogen concentrations were considerably reduced in Cambi AER effluent from Cambi THP-150-15D.

Nitrite and Nitrate Analyses

Presence of nitrite and nitrate was considered to be detrimental to aerobic digestion. The full aeration step led to the drop in pH to 5.8. This was confirmed by the presence of NO_2 in the aerobic digester. The pH drop was attributed to the presence of nitrous acid (HNO_2). Figure 3-12 shows the nitrite values in the aerobic digester and the corresponding ammonia values.

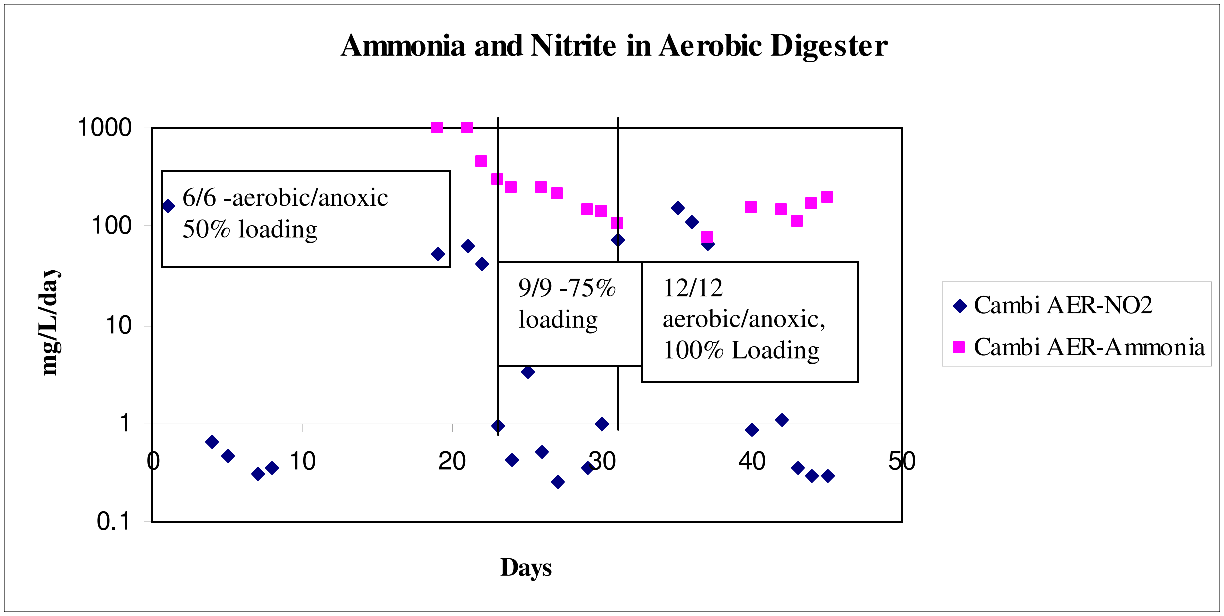


Figure 3-12: Nitrite and Ammonia (mg/L as N) concentration in the aerobic digester.

Aerobic and anoxic phases were operated more carefully to avoid the increase of NO_2. Nitrate was present in small amounts less than 6mg/L in the aerobic digester. To assess the performance of the aerobic digester, nitrite and corresponding ammonia concentrations in aerobic digester were measured on daily basis during shorter time cycles 6/6 (50% loading), 9/9 (75% loading) and 12/12 (100% loading). This was continued until the nitrite was brought down and the removal of ammonia increased to greater than 90%. The nitrite concentrations were high because of presence of nitrous acid and they were brought down. This shows the optimized phase of aerobic digester i.e., during 12/12 time cycle where the ammonia removal is maximum and the nitrite concentrations were very low (less than 1 mg/L).

Dissolved Oxygen and Oxygen Uptake Rates

The dissolved oxygen plays very important role in the operation of the aerobic digester. In the first phase, the DO in the digester was about 1-1.5 ppm and the corresponding ammonia removal was 69%. Figure 3-13 shows the DO profile during aerobic and anoxic phase in Cambi AER-1. The drop in DO occurred when the feed sludge was added. The maximum DO attained in this digester was 1.2 ppm and the minimum was 0.2. As discussed earlier, to attain better ammonia removal, the digester was changed and the oxygen gas cylinder was used for aeration to achieve higher DO in the digester.

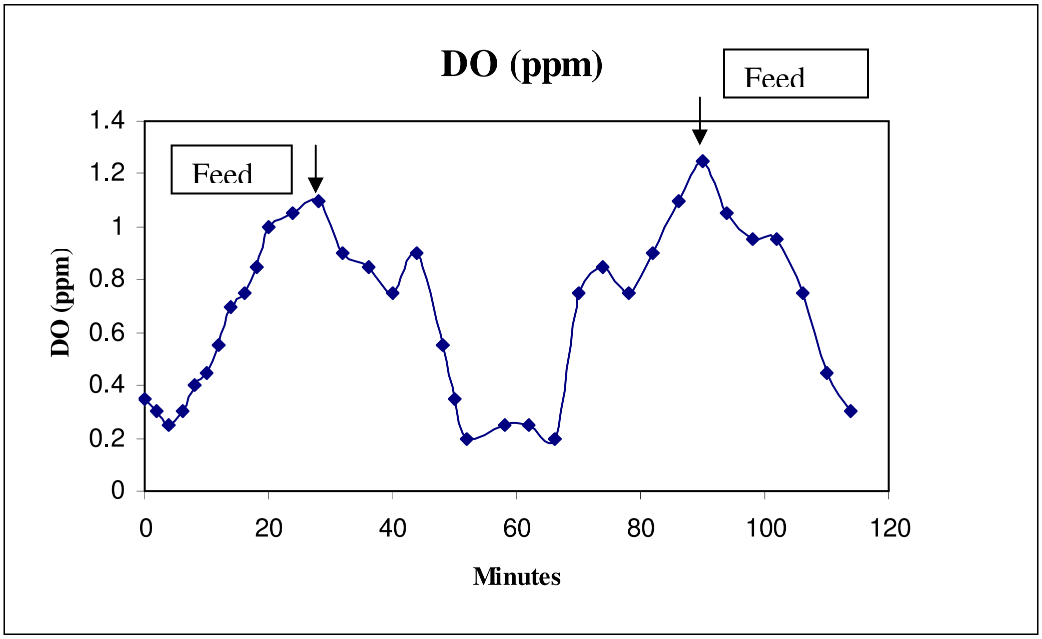


Figure 3-13: Dissolved Oxygen concentrations in Cambi AER-1.

Figure 3-14 shows the typical DO profile for a period 24 hours. Labview 7.1 software and LDO probe were used for these measurements. Figure 3-14 also shows the efficient operation of aerobic phase and anoxic phase. The maximum DO in the aerobic phase was 4 mg/L and minimum DO of 0.5 mg/L was in the anoxic phase.

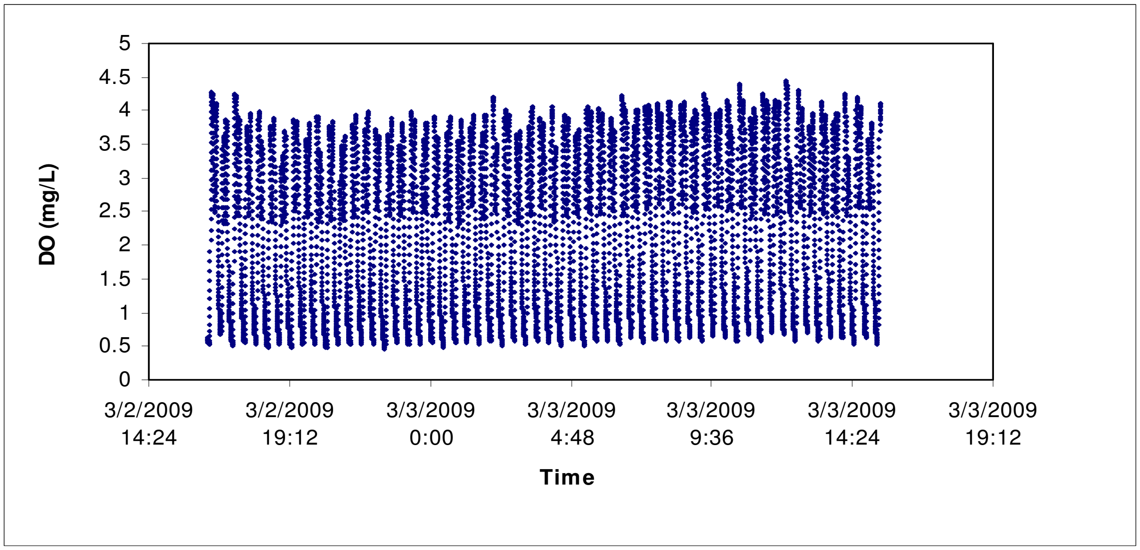


Figure 3-14: Dissolved Oxygen concentrations in Cambi AER-2, typical DO profile in a 24-hr period.

Research has shown that the oxygen uptake rate (OUR) is a promising parameter that can be used to assess the microbial activity and viability of microbes (Huang *et al.,* 1985). The degree of stabilization in the aerobic digester is generally measured using the specific oxygen uptake rate (Grady *et al.,* 1999).

The oxygen uptake rates (OUR) were calculated from this DO data. The slopes were calculated in the anoxic phase and the OUR's were obtained. Figure 3-15 shows the DO values obtained from Lab View 7.1 and LDO probe for aerobic/anoxic phases in a two hour time interval. The reason for two peaks in the figure 3-15 was the program that was developed in Lab View 7.1 for maximum and minimum DO levels, during aeration whenever DO becomes greater than 4 mg/L, the solenoid valve turns off and the air flow stops, this result in dropping of DO. The solenoid valve turns on when the DO is less than 4mg/L and DO starts raising.

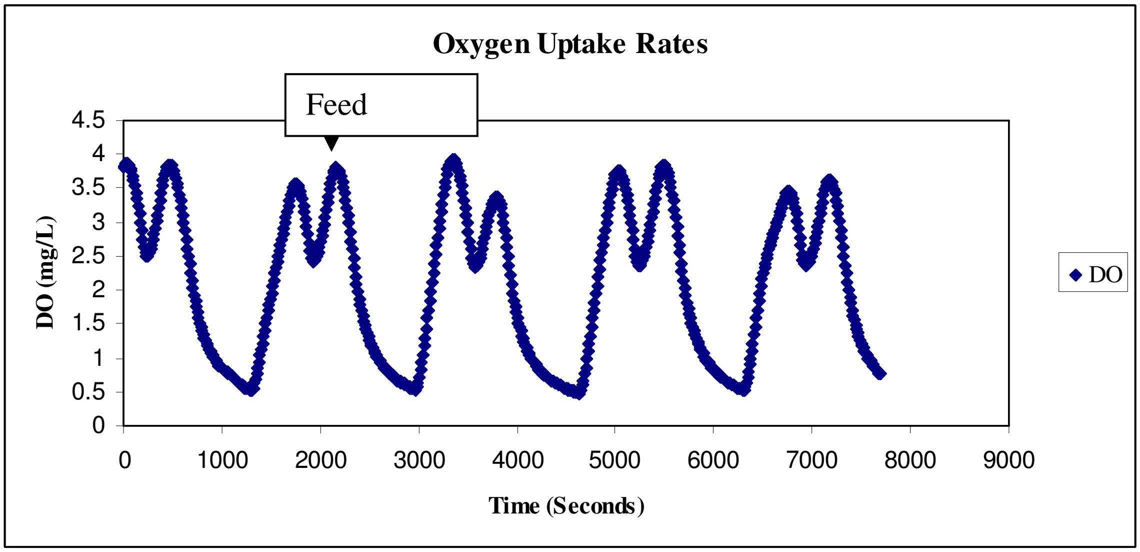


Figure 3-15: Dissolved Oxygen concentrations in aerobic/anoxic phase.

Figure 3-16 shows the OUR data. The oxygen uptake rates for these plots were calculated daily. The OUR's were calculated at DO 4 mg/L for 50% loading, 75% loading and for full loading in the aerobic digester. The OUR was 50 mg/L during full loading and when the ammonia removal is maximum.

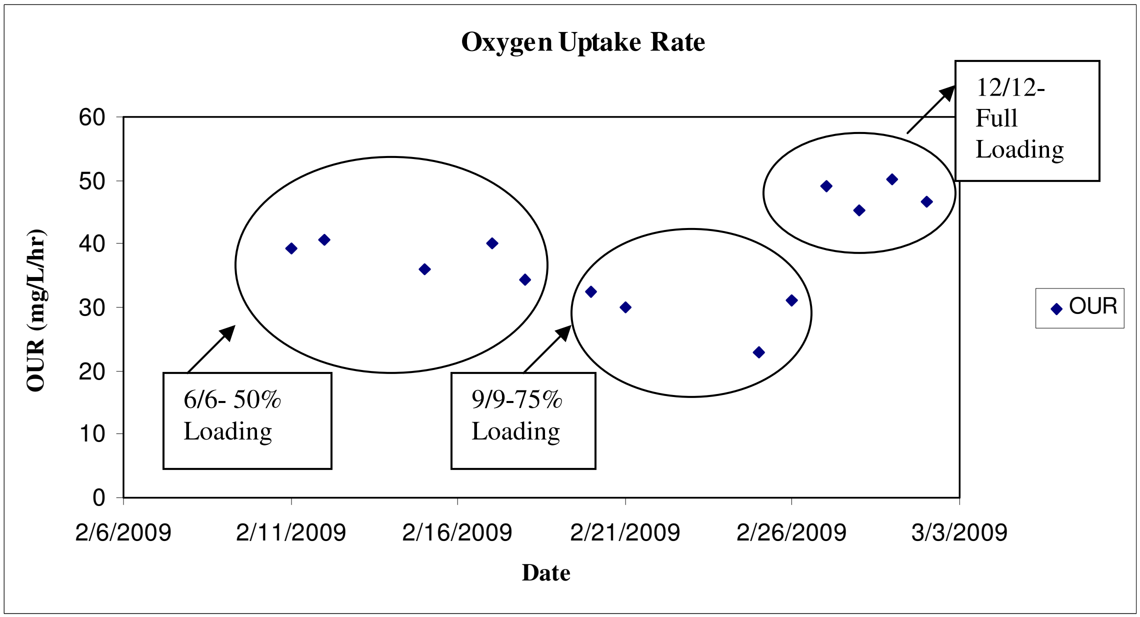


Figure 3-16: Oxygen Uptake Rate (OUR) for aerobic digester.

Volatile Fatty Acid Production and Consumption

Volatile fatty acids are weak acids that are dissociated by neutral pH (Grady *et al.,* 1999). Presence of high VFA's is detrimental to methanogenic activity through their toxic action of un-ionized VFA's and their presence always indicate reactor imbalance. It is always beneficial to maintain favorable pH and moderate VFA concentration so that no drastic effects are imposed on the system (Cohen *et al.,* 1982).

The Cambi processed sludge that was used as feed for anaerobic digester has VFA concentration about 29000 mg/L as HAC, this high VFA's concentration were reduced to 6000 mg/L as HAC after anaerobic digestion (Tanneru *et al.,* 2009). VFA's were also reduced after aerobic digestion. The average VFA concentration in the aerobic digester effluent was 760 mg/L as HAC. Figure 3-17 shows total VFA data and figure 3-18 shows individual VFA's.

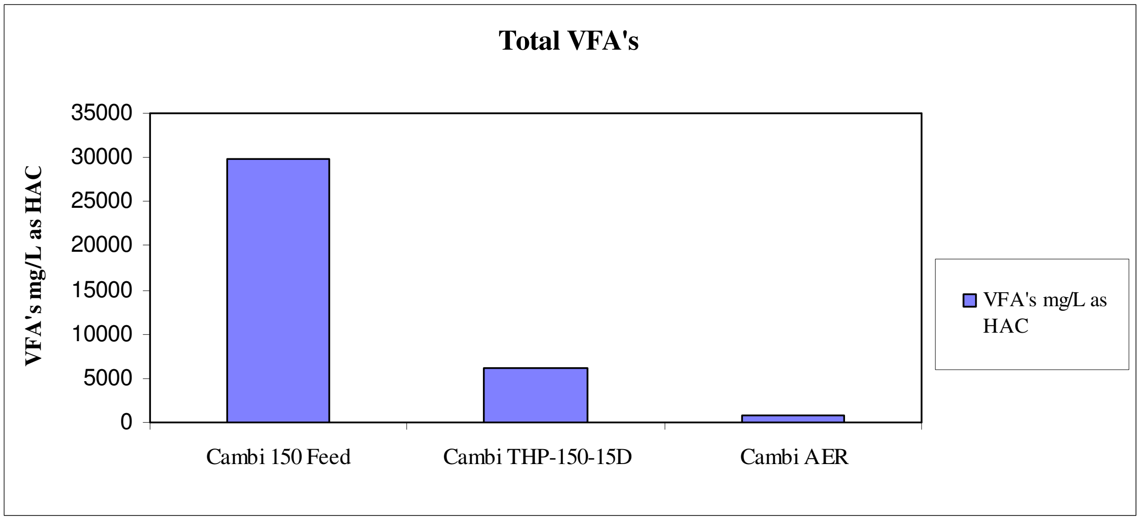


Figure 3-17: Total VFA's in Cambi THP-150 feed, anaerobic digester and aerobic digester.

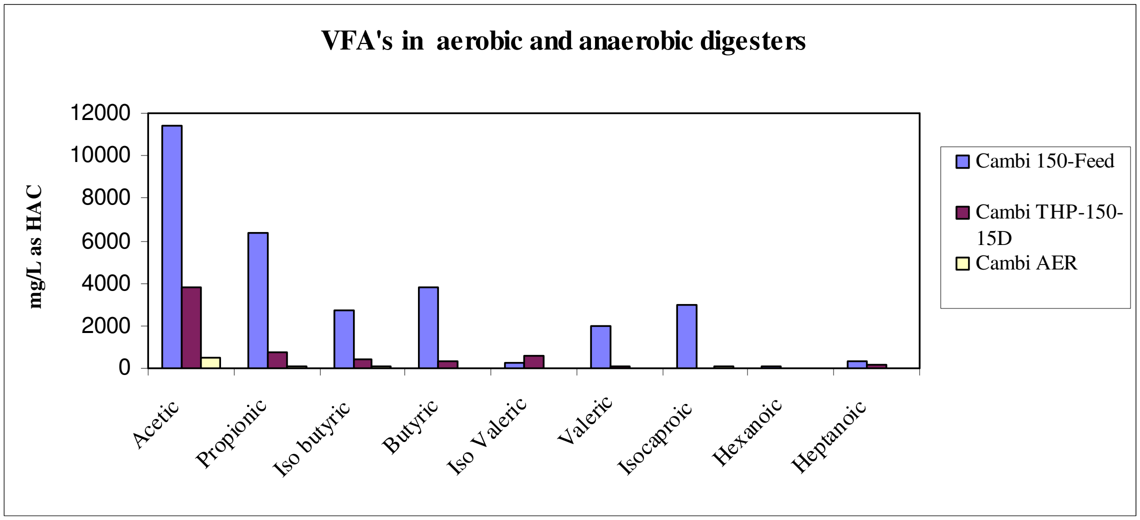


Figure 3-18: VFA's in Cambi THP-150 feed, anaerobic digester and aerobic digester.

The main reason for this VFAs reduction was most probably from the VFA's that has been left out from anaerobic digestion served as carbon source in the denitrification. Of all the VFA's that were present acetic acid was of greater amount followed by propionic acid. The maximum acetic acid concentration and corresponding lower concentration of other longer chain VFA's suggests that the acetic acid is being produced from all other longer chain VFA's. Thus, the data show that the shorter chain VFA's served as primary carbon source during denitrification.

Optimum Polymer Dose and Cake Solids Concentration

The figures 3-19 and 3-20 show the polymer dose and total cake solids concentration for Cambi THP-150-15D and Cambi AER. The data shows that polymer dose of aerobic digester is higher than anaerobic digester.

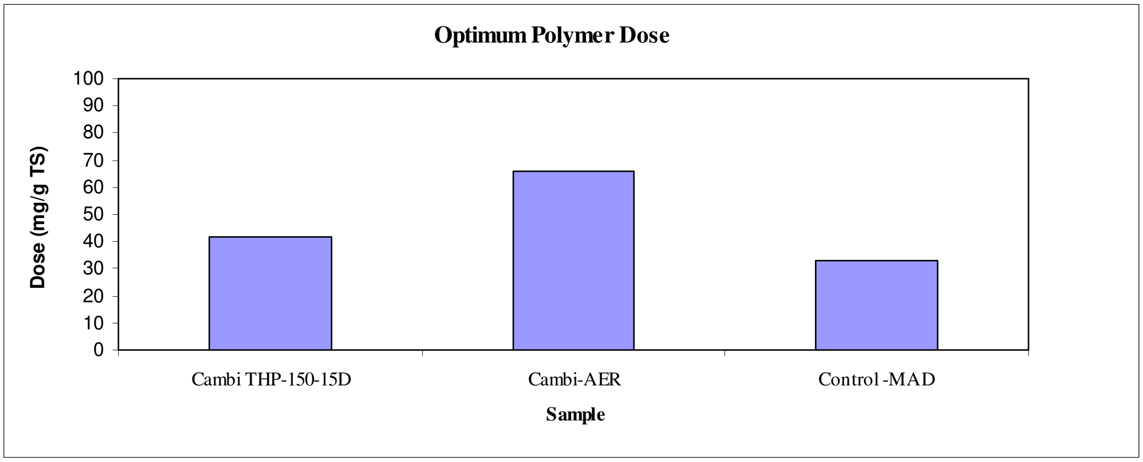


Figure 3-19: Comparison of Optimum Polymer Dose between Cambi aerobic, anaerobic digester and Control-MAD.

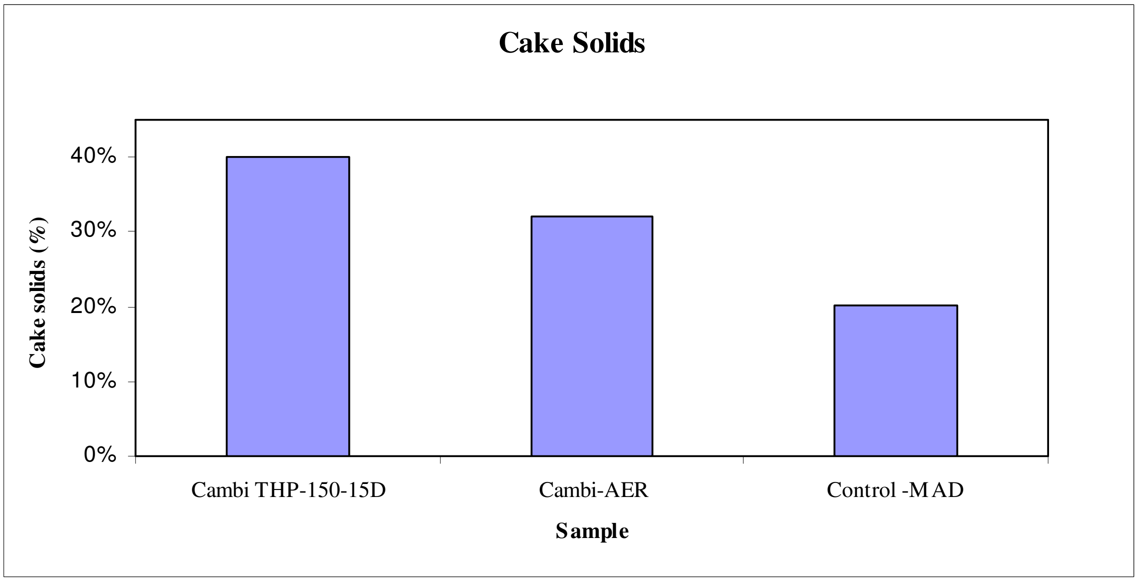


Figure 3-20: Comparison of Cake Solids concentrations between Cambi aerobic, anaerobic digester and Control-MAD.

The data for Cambi THP-150-15D and Control-MAD was obtained from Tanneru *et al.,* (2009) and Banjade (2008). The cake solids concentration data shows that, doing Cambi pretreatment increased the cake solids concentration for both anaerobic and aerobic digesters compared to Control-MAD.

Odor Analyses

Odorous emissions from sewage systems and WWTP's can cause serious problems in the vicinity of the plant. Odorants present in the liquid phase are emitted into the ambient air at the liquid-gaseous interface (Frechen *et al.,* 1998). Generally anaerobic digestion is used to process sludge for land application, but research has shown that anaerobic digestion and dewatered biosolids cakes can generate unacceptable odors (Murthy *et al.,* 2002). The main odor causing chemicals were found to be volatile inorganic sulfur compounds and volatile organic sulfur compounds (VOSC) which include carbon disulfide, hydrogen-sulfide (H_2S), methanethiol (MT), dimethyl sulfide (DMS), dimethyl disulfide (DMDS) and trimethyl amine. Methanogens play a key role in the degradation of VOSC's (Novak *et al.,* 2006, Higgins *et al.,* 2006, Kim *et al.,* 2002).

VOSC's were measured for both anaerobically digested sludge and aerobically digested sludge, with and without adding bromo ethane sulfonic acid (BESA) and are shown in figures 3-21 and 3-22. Figure 3-21 shows the peak total volatile organic sulfur compounds (TVOSC) values for aerobic sludge, Cambi THP-150-15D sludge and conventionally digested sludge.

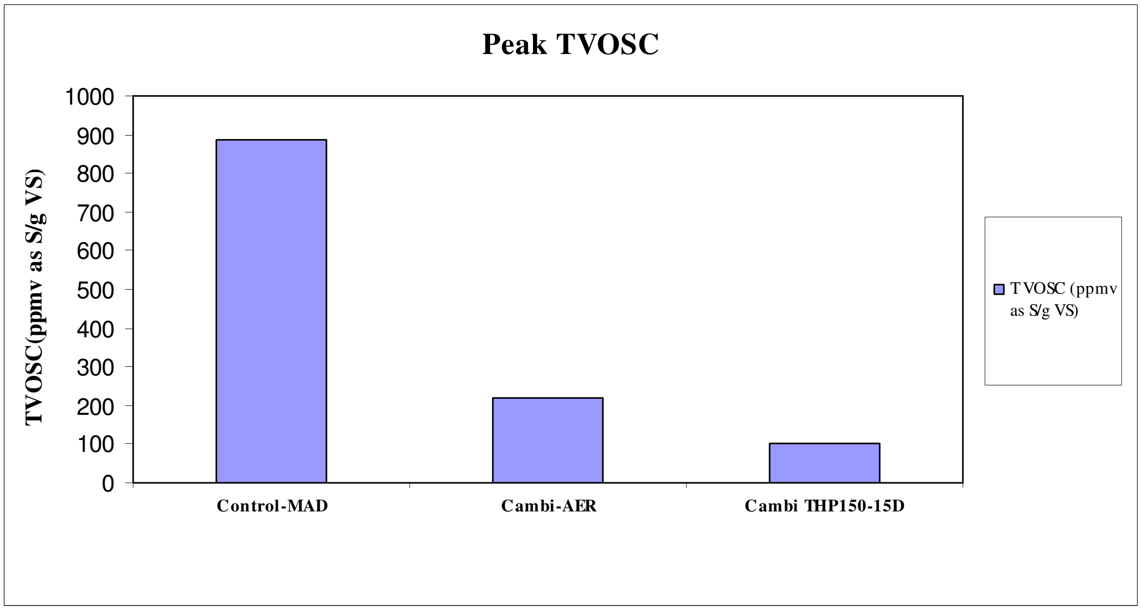


Figure 3-21: Peak TVOSC values for Cambi anaerobic and aerobic digesters, without BESA.

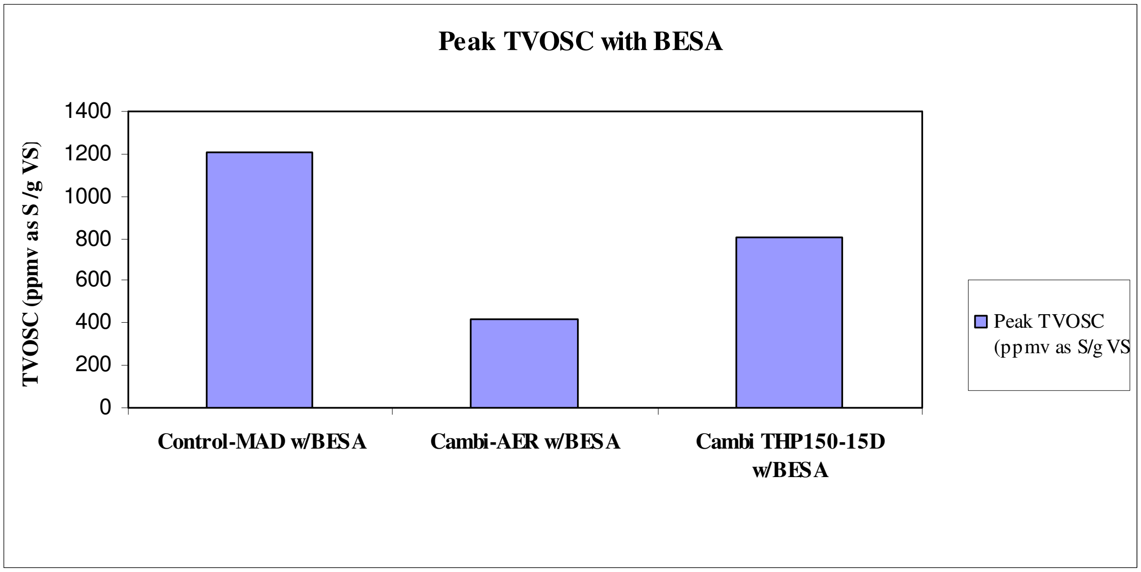


Figure 3-22: Peak TVOSC values for Cambi anaerobic and aerobic digesters, with BESA.

The peak TVOSC of aerobically digested sludge was slightly higher than anaerobically digested sludge. This is because of lack of methanogens in aerobic sludge. The peak TVOSC values for BESA samples were higher compared to normal samples because of the inhibition of methanogenisis by BESA.

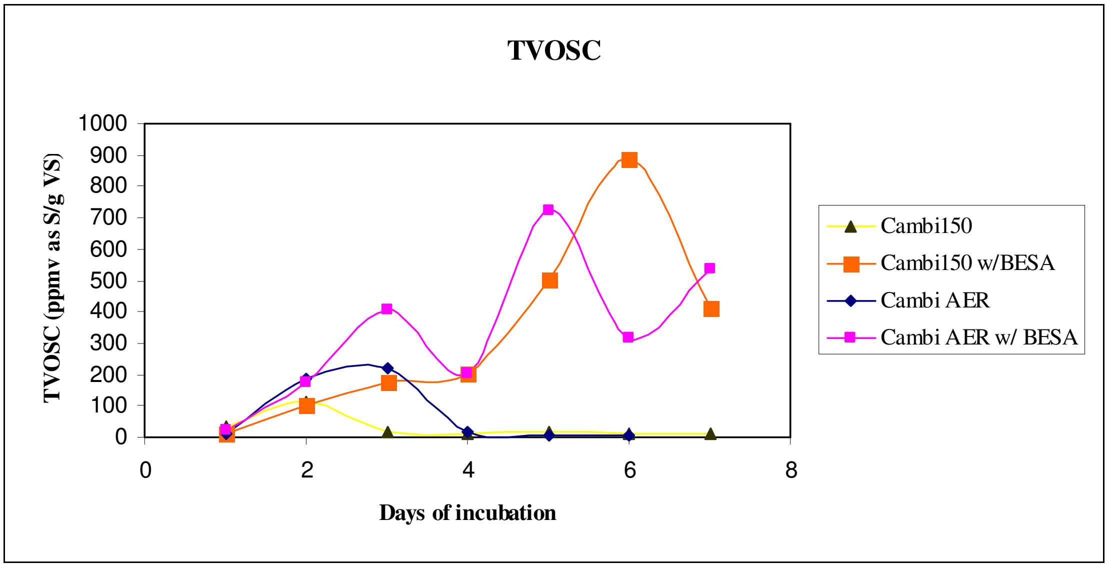


Figure 3-23: TVOSC values for Cambi anaerobic and aerobic digesters, with and without BESA.

Anaerobically digested sludge peaked in 2 days and aerobically digested sludge peaked in 3 days.

3.6 Conclusions

The objective of this research was to study the advantages and disadvantages of aerobic digester with aerobic phase and anoxic phase. The digester was fed with cambi pretreated anaerobically digested sludge. The following conclusions were drawn from the study.

1. **Cambi aerobic digester gave additional VS reduction (8-10%) than Cambi anaerobic digester.**

Cambi aerobic digester gave overall VS reduction of 69% and Cambi THP-150 gave VS reduction of 58%, this is 11% higher from the anaerobic digestion.

2. **Cambi aerobic digester gave additional COD reduction (12-15%) than Cambi anaerobic digester.**

Cambi aerobic digester gave overall COD reduction of 69% and Cambi THP-150 gave COD reduction of 55%, this is 14% higher.

3. Cambi aerobic digester accomplished 92% overall ammonia removal

The cambi aerobic digester was very successful in removing ammonia that has been developed during anaerobic digestion. It gave about 92% over all removal. The reject water can be sent to the beginning of the plant without ammonia.

References

Akunna, Joseph., Bizeau, Claude., Moletta, René., Bernet, Nicolas., and Héduit, Alain. Combined Organic Carbon and Complete Nitrogen Removal Using Anaerobic and Aerobic Upflow Filters. *Wat. Sci. Tech. Vol. 30, No. 12, pp. 297-306, 1994.*

Al-Ghusian, Ibrahim., and Hao, Oliver J. Use of pH as Control Parameter for Aerobic/Anoxic Sludge Digestion. *Journal of Environmental Engineering, Vol. 121, No. 3, 1995.*

APHA, AWWA, and WPCF. Standard Methods for the Examination of Water and Wastewater, 20th Ed.; Washington, D.C. 1998.

Banjade, Sarita. Anaerobic/Aerobic Digestion for Enhanced Solids and Nitrogen Removal. *Master's Thesis, Virginia Polytechnic Institute and State University, 2008.*

Batchelor, B. Simulation of single-sludge nitrogen removal. *Journal of Environmental Engineering 109, 1-16, 1983.*

Cohen, A., Breure, A. M., van Andel, J. G., and A. van Deursen. Influence of Phase Separation on the Anaerobic Digestion of Glucose-II. *Water Res. Vol. 16, pp. 449-455, 1982.*

Frechen, Franz-Bernd., and Köster, Wulf. Odour Emission Capacity of Wastewaters-Standardization of Measurement Method and Application. *Wat. Sci. Tech. Vol. 38, No. 3, pp. 61-69, 1998.*

Ganczarczyk, J., Hamoda, M. F., and Wong, Hong-Lit. Performance of Aerobic Digestion at Different Sludge Solid Levels and Operation Patterns. *Water Research, Vol. 14, pp. 627 to 633, 1980.*

Glindemann D, Murthy SN, Higgins MJ, Chen YC and Novak JT. Biosolids incubation method for odorous gas measurement from dewatered sludge cakes. *Journal of Residuals Science & Technology 3(3), 153-160, 2006.*

Grady, C.P. Leslie, Daigger, Glen T., Lim, H.C., Biological Wastewater Treatment, *Marcel Dekker, New York, 1999.*

Higgins, Matthew J., Chen, Yen-Chih., Yarosz, Douglas P., Murthy, Sudhir N., Maas, Nick A., Glindermann, Dietmar., and Novak, John T. Cycling of Volatile Organic Sulfur Compounds in Anaerobically Digested Biosolids and its Implications for Odors. *Water Environment Research, Volume 78, Number 3, 243-252, 2006.*

Huang, Jerry Y. C., Cheng, Meng-Dawn., and Mueller, James T. Oxygen Uptake Rates for Determining Microbiological Activity and Application. *Water Res., Vol. 19, No 3, pp. 373-381, 1985.*

Khalili, Nasrin R., Chaib, Embarka., Parulekar Satish J., and Nykiel , David. Performance enhancement of batch aerobic digesters via addition of digested sludge. *Journal of Hazardous Materials, B76, 91-102, 2000.*

Kim, H., Murthy, S., McConnell, L. L., Peot, C., Ramirez, M., and Strawn, M. Characterization of wastewater and solids odors using solid phase microextraction at a large wastewater treatment plant. *Water Science and Technology Vol. 46, No. 10, pp. 9-16, 2002.*

Kumar, N. Sequential Anaerobic-Aerobic Digestion: A new process technology for biosolids product quality improvement. *Master's Thesis, Virginia Polytechnic and State University, 2006.*

Li, H., Liang, X., Yingxu, Chen., Yanfeng, Lian., Guangming, Tian., and Wuzhong, Ni. Effect of nitrification inhibitor DMPP on nitrogen leaching, nitrifying organisms, and enzyme activities in a rice-oilseed rape cropping system. *Journal of Environmental Sciences 20(2): 149-155, 2008.*

Matsuda, Akira., Ide, Tetsuo., and Fujii, Shozo. Behavior of Nitrogen and Phosphorus during Batch Aerobic Digestion of Waste Activated Sludge – Continuous Aeration and Intermittent Aeration by Control of DO. *Wat. Res. Vol. 22, No. 12, pp. 1495-1501, 1988.*

Murthy, S. N., Forbes, B., Burrowes, P., Esqueda, T., Glindemann, D., Novak, J., Higgins, M. J., Mendenhall, T., Toffey, W., Peot, C. Impact of High Shear Solids Processing on Odor Production from Anaerobically Digested Biosolids. Proceedings of the 75th Annual Water Environment Federation Technical Exposition and Conference, Chicago, Illinois, Water Environment Federation, Alexandria, Virginia, 2002.

Novak, John T. Dewatering of Sewage Sludge. *Drying Technology, 24: 1257-1262, 2006.*

Parravicini, V., Smidt, E., Svardal, K., and Kroiss, H. Evaluating the stabilization degree of digested sewage: investigations at four municipal wastewater treatment plants. *Water Science & Technology Vol. 53 No. 8 pp. 81-90, 2006.*

Parravicini, V., Svardal, K., Hornek, R., and Kroiss, H. Aeration of anaerobically digested sewage sludge for COD and nitrogen removal: optimization at large scale. *Water Science & Technology-WST, 57.2, 2008.*

Spinosa, L., and Vesilind P. Aarne. Sludge into Biosolids: Processing, Disposal and Utilization. *IWA Publishing, Alliance House, 12 Caxton Street,London SW1H0QS, UK, 2001.*

Tanneru, Charan Tej., John T. Novak., Anaerobic Digestion of Thermally Hydrolyzed Sludge, 2009. *Master's Thesis, Virginia Polytechnic Institute and State University, 2009.*

Tchobanoglous, G., Burton, F.L., Stensel, H.D. Wastewater Engineering: Treatment and Reuse. *Metcalf & Eddy Inc., 4th Ed., McGraw-Hill, New York, 2003.*

Tyagi, R. D., Tran, F. T., and Agbebavi, T. J. Mesophilic and Thermophilic Aerobic Digestion of Municipal Sludge in an Airlift U-Shape Bioreactor. *Biological Wastes 31, 251-266, 1990.*

U.S. EPA. Environmental Regulations and Technology - Control of Pathogens and Vector Attraction in Sewage Sludge. *EPA/625/R-92/013, 2003*.

Warner, A. P. C., Ekama, G. A., and Marais, G. V. R. The Activated Sludge Process – IV: Application of the General Kinetic Model to Anoxic-Aerobic Digestion of Waste Activated Sludge. *Wat. Res., Vol. 20, No. 8, pp. 943-958, 1986.*