Comparative Studies of Alternative Anaerobic Digestion Technologies

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Abstract

Washington D.C. Water and Sewage Authority is planning to construct a new anaerobic digestion facility at its Blue Plains WWTP by 2008. The research conducted in this study is to aid the designers of this facility by evaluating alternative digestion technologies. Alternative anaerobic digestion technologies include thermophilic, acid/gas phased, and temperature phased digestion. In order to evaluate the relative merits of each, a year long study evaluated the performance of bench scale digestion systems at varying solids retention times (SRT) and organic loading rates (OLR). The digesters were fed a blend of primary and secondary residuals from the Blue Plains wastewater treatment facility.

In each study phase, temperature phased anaerobic digestion was compared to single stage mesophilic digestion (the industry standard) at the same SRT. Single stage thermophilic digestion was evaluated by sampling the first thermophilic stage of the temperature phased digestion systems throughout the study. Additionally, the first phase study compared acid/gas phased digestion to temperature phased and single stage mesophilic digestion.

Results of the study demonstrated that the temperature phased digestion system consistently performed better than the other systems during each study phase by having higher volatile solids reduction (VSR), higher methane production, and lower residual biological activity. The highest observed VSR during the study (67%) occurred in a temperature phased digestion system operated at 7.5 days in each stage. Based on these results, it seems a suitable candidate for the Blue Plains digestion facility. Additionally, odor studies performed in conjunction with the research presented in this paper have shown distinct advantages for the temperature phased process.

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Dedication

To my wife, Sara: Thank you for your love, patience, and willingness to leave the familiar and support me in this pursuit. I look forward to the next phase of our lives together.

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Literature Review

Introduction

Modern wastewater treatment plants frequently utilize biologically mediated processes to remove organic matter and nutrients before discharge to the environment. With the development of the activated sludge process in the late 1800's and early 1900's (Alleman and Prakasam, 1983), and continual refinements to process since then, the wastewater treatment process is now robust and capable of producing a high quality effluent. One problematic aspect of the modern wastewater treatment process is the disposal of treatment residuals. Two residual products are generated during wastewater treatment. The first is dense, insoluble organic matter that settles in primary settling processes (primary sludge). The second is the biomass and insoluble organic matter generated in the wastewater bioreactors and separated in final settling operations (secondary sludge) (Grady et al., 1999).

Environmental laws and public health concerns dictate that the residuals generated during wastewater treatment undergo further treatment before ultimate disposal. Municipal wastewater works frequently use anaerobic bioreactors, a.k.a. digesters, to accomplish further treatment. The purpose of anaerobic digestion of wastewater residuals is to stabilize it by reducing the organic matter so that minimal decay occurs upon disposal. During the stabilization process, odor reduction, pathogen reduction, and mass reduction are also achieved (Parkin and Owen, 1986). Furthermore, a product of anaerobic metabolism is methane, a useful energy source.

Anaerobic metabolism

The consortia of microorganisms that make up the biomass of an anaerobic digester include general classes of microorganisms called the acetogens and methanogens. However, many microorganisms are found in anaerobic digester biomass and all play an important role in the biochemical reactions that degrade wastewater residuals. Figure 1 summarizes some of the more important biochemical reactions that occur in anaerobic sludge digesters.

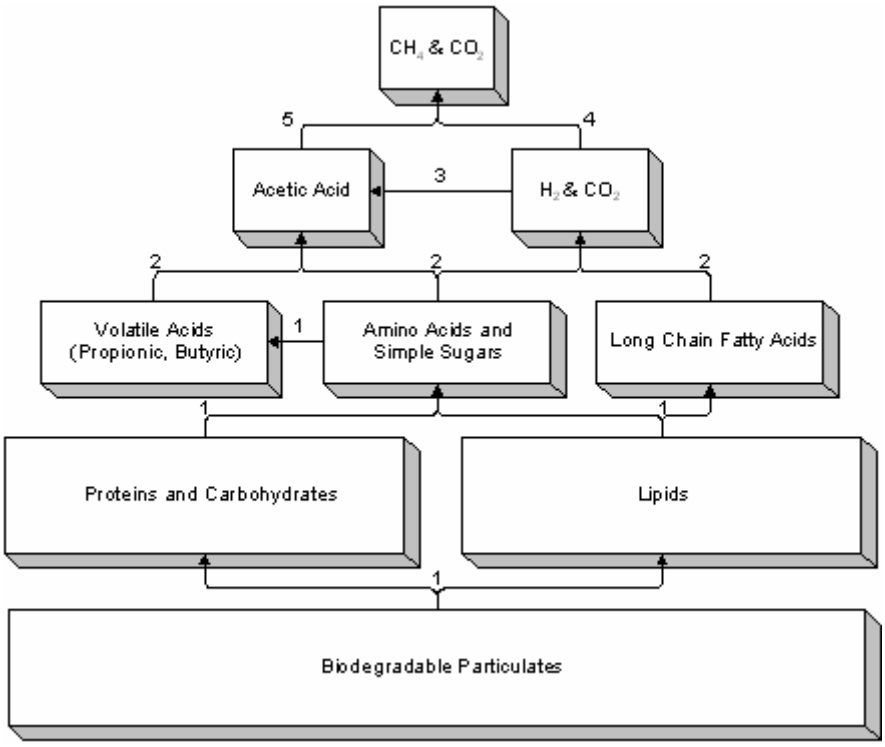

Figure 1 - Compounds and biochemical reactions occurring in sewage sludge digestion. Important microorganisms include: 1) Fermentative bacteria 2) H_2-producing acetogens 3) H_2 consuming acetogens or homoacetogens 4) CO_2 reducing methanogens 5) Acetoclastic methanogens (Novaes, 1986).

Efficient digester performance requires all of these metabolic pathways to function well. One clever analogy for this concept is that of a bucket brigade transferring buckets of water to put out a fire: Each member of the brigade is important to the overall goal and inefficiency occurs when one member is not functioning properly (Speece, 1996).

Just as members of a bucket brigade should stay close so they can efficiently transfer water buckets, it seems that certain members of the sludge digester community benefit from close proximity to transfer their metabolic intermediates. A well-documented example is the consortia of methanogens and acetogens. Hydrogen partial pressure in the bulk liquid of a digester can exceed levels that favor the thermodynamics of propionate conversion by acetogens to acetate and hydrogen and the conversion of hydrogen by methanogens to methane (Grady et al., 1999). It is hypothesized that the metabolism of propionate in sludge digesters is dependent on the close proximity of methanogens and acetogens. Destroying this proximity can cause a build up of

propionate and butyrate and the digester can become unstable or even fail due to a subsequent decrease in pH (Parkin and Owen, 1986).

Developments in digestion

Before digesters were used, anaerobic treatment of residuals occurred to some extent in sludge storage tanks at wastewater facilities. History is inconclusive whether German or UK municipal wastewater works were the first to build anaerobic digesters for the express purpose of residuals treatment in the 1930's (Noone, 1990). Designers sought to enhance the natural microbial activity with heating and mixing, usually at mesophilic (30-40°C) temperatures.

Today, digestion performed in a single stage mesophilic digester is the common method utilized for residuals stabilization in municipal wastewater treatment. Biosolids are the byproduct of residuals stabilization. In the past several decades, practitioners have looked to alternative technologies to improve digestion performance and produce higher quality biosolids.

Land application laws and public health concerns have driven the development of technologies to reduce pathogens in digested biosolids. For example, the US EPA implemented standards in 40 CFR Part 503 (1993) that govern biosolids disposal based on the pathogen reduction criteria. The 40 CFR Part 503 regulation is a technology based standard and defines the processes suitable to achieve Class A and Class B biosolids. Class A biosolids, those treated with a process that reduces pathogen levels below detectable limits, have few restrictions for ultimate disposal. Biosolids with pathogen levels above detectable limits, termed Class B biosolids, must be disposed of on restricted sites.

In addition to pathogen reduction goals, rising transportation, disposal, and handling costs have driven the search for digestion processes that have higher volatile solids reduction and better dewaterability in biosolids. Some alternative anaerobic digestion technologies include thermophilic digestion, acid/gas phased digestion, and temperature-phased digestion. These processes can destroy more volatile solids, produce more methane, and reduce pathogens, sometimes to a point capable of meeting Class A biosolids standards. They are of increasing interest to regulators and the wastewater industry.

Thermophilic Digestion

Thermophilic digestion is one example of an alternative technology, though it is by no means a newly developed process. The main interest in thermophilic digestion is due to its pathogen reducing potential that was documented at least 75 years ago (Rudolfs and Heulekian, 1930). Other cited advantages of thermophilic treatment over mesophilic treatment include higher reaction rates, better dewaterability, and increased volatile solids reduction (VSR)(Buhr and Andrews, 1977).

Some of the earliest full-scale studies of thermophilic digestion in the U.S. occurred at the Hyperion WWTP in Los Angeles, CA, from 1953 to 1957 (Garber, 1954). The thermophilic digesters at Hyperion treated a blend of primary and waste activated sludges (70:30 ratio) and were operated at several different organic loading rates. Results demonstrated that thermophilic digestion was capable of destroying equal or more volatile solids than digesters operated at mesophilic temperatures. Subsequent studies at Hyperion showed that thermophilic digester produced biosolids that were easier to dewater but the supernatant had higher levels of volatile fatty acid than the mesophilic digesters (Garber et al., 1975).

High volatile fatty acids in the effluent are frequently cited as a problem with thermophilic digestion, causing malodorous waste streams that are difficult to handle (WEF, 1987). Moen et al. (2003) tested mesophilic and thermophilic digesters at varying solids retention time (SRT) and organic loading rate (OLR) conditions. The digesters in this study treated a blend of primary and waste activated sludges. Their results demonstrated that volatile fatty acids (VFA) increased with decreasing SRT, ranging from around 400 mg/L at 20 day SRT to over 2500 mg/L at the 4 day SRT. The acetic acid concentration was higher than the propionic acid concentration in all but the 4 day SRT, where propionate was the dominant species of VFA. High effluent volatile fatty acids might be due to a flawed operational approach of thermophilic digesters. Kim et al. (2002) showed that a non-mixed thermophilic reactor treating dog food (similar to primary sludge) had equal VSR to a mixed thermophilic reactors, but produced much less effluent propionic acid and total VFA. The non-mixed thermophilic reactor in Kim et al.'s study also had higher VSR, produced more biogas, and was able to operate at a higher OLR until failure than the mesophilic digesters.

Researchers do not always observe higher volatile solids reduction in thermophilic treatment. Data from Moen et al.'s study suggested that at SRT of 10 days or longer there was no difference in VSR between mesophilic and thermophilic digesters. They concluded that volatile suspended solids (VSS) reduction may be more suitable for comparison because soluble COD levels were higher in the thermophilic reactor than in the mesophilic digester, causing an error in the volatile solids test procedure. If soluble COD levels are similar in digesters, there would be no error associated with comparing VSR. Based on VSS reduction, they demonstrated slightly better performance from the thermophilic reactor at 6, 10, and 15 day SRT.

Higher destruction of organics can sometimes be problematic in thermophilic digestion because of the protein content of the influent. Too much protein degradation in thermophilic digestion may cause ammonia inhibition of the thermophilic biomass. This may be a potential disadvantage to thermophilic digestion versus mesophilic digestion. Sung and Liu (2003) reported the chronic and acute toxicity effects of ammonia on thermophilic biomass in 7 day SRT reactors treating non-fat dry milk. They operated these digesters at various loading rates and sequentially increased the total ammonia nitrogen levels in the feed. Results demonstrated that the specific methane yield generally decreased as the feed ammonia nitrogen level was increased. Through modeling simulations, it was also demonstrated that acclimation to increased total ammonia nitrogen levels diminished the effects of ammonia inhibition on specific methane yield in thermophilic digesters. Their study demonstrated the complex interaction between pH and unionized ammonia concentration as it relates to biomass toxicity. Since the pKa of ammonia is inversely proportional to temperature, it seems reasonable that at lower temperatures, the toxicity effect of unionized ammonia might diminish, though Sung and Liu did not investigate that possibility.

Acid/Gas Phased Digestion

Drawing on the growing knowledge of anaerobic microorganism metabolisms, Pohland and Ghosh (1971) first proposed acid/gas phased digestion. In acid/gas phased digestion, operators can vary the SRT to kinetically select for either acid-forming or methane-forming microorganisms (Massey and Pohland, 1978). Methane-forming microorganisms, having a slow growth rate, are washed out of a digester if the SRT is

low enough. The low SRT and high organic loading causes an accumulation of organic acid intermediates in the first digester. As the digester pH drops, conditions become favorable for the growth of acid-formers, which have an optimum growth rate at around pH 6 (Dichtl, 1997). Accordingly, the first digester in acid/gas-phased systems is operated at a low SRT (12 hours-1.5 days) to promote the growth of acid-forming micro-organisms, while the following digester has a high SRT (≥18 days) to allow for the establishment of a methane-forming biomass. Acid/gas phased digestion has been applied successfully in several full-scale operations (Wilson and Dichtl, 2000).

The principal advantage cited for acid/gas phased digestion is the ability to optimize hydrolysis and acidogenesis reactions in the acid reactor and acetogenesis and methane formation in the gas phase digester. This reportedly enhances reaction kinetics, makes pH control easier, improves the ability of the system to absorb shock load, and detoxifies influents that may harm the sensitive methane formers in the second phase (Fox and Pohland, 1994). Fox and Pohland also suggest that disadvantages to phase separation may include disrupting the syntrophic relationship between hydrogen formers and hydrogen utilizers that is important to the anaerobic digestion process. Partial phase separation could overcome some of these disadvantages and they concluded that the decision for using a complete or partially separated phase separated process must be on a case-by-case basis.

Studies suggest improved performance of acid/gas phased digestion versus single stage digestion (Ghosh, 1987) as measured by volatile solids reduction, methane yield, and effluent VFA composition. Ghosh determined in this study that a mesophilic acid/gas system was able to destroy equivalent volatile solids to a single stage digester operated at 15 and 17 day SRT.

Studies on acid/gas phased digestion often incorporate thermophilic digestion in one of the phases. This makes it difficult to assess temperature variation effects versus phase separation effects on anaerobic digestion performance. Thermophilic temperature regimes were studied in the acid/gas configuration of Ghosh's work (1987), but he concluded that lipid and protein metabolites inhibited acetogenesis and methanogenesis in the thermophilic digester. When both stages are mesophilic, however, the biosolids do not meet the EPA's time and temperature requirements for Class A biosolids. Certain

systems, such as the two phase anaerobic digestion process (2PAD), seek to incorporate complete phase separation and thermophilic digestion in the first reactor (Huyard et al., 2000) in order to meet Class A biosolids requirements. Complete phase separation is achieved in the 2PAD digester by chemically lowering the pH to a level that is ideal for acid formers and harmful to methanogens.

Temperature Phased Digestion

Another alternative digestion technology seeks to combine the benefits of the thermophilic digestion process and partial phase separation instead of complete phase separation as in the 2PAD process. This technology is called temperature-phased anaerobic digestion (TPAD) in the U.S. (Dague et al., 1996) and the Anaerobic Stabilization Thermophilic/Mesophilic system (ASTM) in Europe (Oles et al., 1997). In temperature-phased digestion, the temperature is varied between digesters to select for mesophilic or thermophilic microorganisms. Digesters are usually operated from 30-38° C for mesophilic conditions and 50-60°C for thermophilic.

Partial phase separation is accomplished in the first thermophilic stage of the TPAD process by lowering SRT. The argument is that true phase separation cannot occur in thermophilic digestion because thermophilic temperatures preclude the development of a sole acid-forming stage (Dichtl, 1997). Because of this, Dichtl suggests that a thermophilic digester in the TPAD system should be operated between 3 and 5 days, which achieves an adequate balance between acid-formers and methane-formers and minimizes propionic acid accumulation. Commonly, TPAD processes include a thermophilic reactor (3-5 day SRT) followed by a mesophilic digester (>18 days) (Metcalf and Eddy, 2003).

Han and Dague (1997) demonstrated 18% higher VSR and methane production from a TPAD process versus a single stage mesophilic digester across a range of SRT from 10 to 15 days. Yet improved volatile solids reduction may come at the cost of poor dewatering. Bivins and Novak (2001) observed poor biosolids dewatering characteristics in a bench-scale TPAD system: Dewaterability, as measured by capillary suction time and optimal polymer dose, became worse when the 1st stage thermophilic reactor was increased from a detention time of 1.5 to 3 days. Nevertheless, class A biosolids production capability may outweigh the disadvantage of poor dewatering characteristics.

Vandenburgh and Ellis (2002) showed a TPAD process capable of meeting Class A biosolids requirements across a range of solids loading conditions. The first stage thermophilic reactor in their study also tolerated high levels of un-ionized ammonia (326 mg/L), suggesting its suitability for treatment of high nitrogen wastes. As later studies have suggested, this tolerance of un-ionized ammonia may be due to acclimation of the thermophilic biomass (Sung and Liu, 2003). An ammonia tolerant thermophilic biomass would certainly be advantageous to a wastewater treatment facility that generates high nitrogen sludges during biological nutrient removal.

Schmit and Ellis (2001) compared the performance of TPAD digestion to 2PAD digestion while digesting mixed primary sludge and municipal solid waste. The distinguishing characteristic between the two systems was that the 1st stage thermophilic digester of the 2PAD system was operated at pH of 5.6 and the 1st stage thermophilic digester of the TPAD system was operated at pH 7. Both systems had total system SRT of 13 days initially, but were later switched to 15 days. Results demonstrated that when the feed had up to 60% of the organic fraction of solid waste, the TPAD system destroyed more VS and had a higher specific methane yield. When the organic fraction of municipal solid waste was higher than 60% in the influent, the performance of TPAD and 2PAD digesters was similar. This is reflective of Fox and Pohland's comments regarding substrate specificity when considering the appropriateness of complete or partial phase separation.

Summary

While thermophilic digestion has demonstrated capability of reducing pathogens to a point suitable for production of Class A biosolids, the EPA has not listed it as an alternative technology suitable for this purpose because of operational stability issues (Metcalf and Eddy, 2003). Fluctuating volatile fatty acid (VFA) levels, odorous effluent, and foaming problems have all been attributed to thermophilic digester operation (WEF, 1987). A better understanding of optimal operating conditions may one day minimize such problems.

Acid/gas phased digestion may have certain advantages over single stage digestion. However, the suitability of acid/gas phased digestion will depend on the nature of the waste being treated as certain wastes may upset environmental conditions

that are important for methane formation (Fox and Pohland, 1994). Acid/gas phased digestion may be conducted at thermophilic temperatures, such as in the 2PAD system, but studies are unclear as to whether the advantages in such systems come from temperature variation or phase separation.

Temperature phased digestion takes advantage of phase separation and thermophilic digestion. While the EPA lists it as a suitable technology for producing Class A biosolids, relatively few full scale installations are in operation in the United States. Studies suggest that the TPAD process can alleviate some of the problems associated with single stage thermophilic digestion, such as high effluent VFA. Furthermore, TPAD digesters that utilize a first stage thermophilic digester may be appropriate for treating certain wastes due to the advantages of thermophilic temperatures and partial phase separation.

Though the practical objective of the research conducted for this thesis work is to help Blue Plains determine design parameters for the construction of a new anaerobic digestion facility, it is of academic interest as well. It is difficult to find any studies that compare TPAD digestion to acid/gas phased separation performed at mesophilic temperatures digesting a blend of waste activated and primary sludge. In this regard, the research conducted as part of this thesis is unique.

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Manuscript 1

Comparing Acid/Gas-Phased to Temperature-Phased and Conventional Mesophilic Digestion

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Abstract

Performance of three bench scale anaerobic digestion systems was compared during this study. The systems studied were acid/gas phased (both digesters mesophilic), temperature phased (thermophilic/mesophilic), and single stage mesophilic digestion. All three systems operated at 20-day solids retention time (SRT) and were fed a blend of primary and secondary residuals from the Blue Plains wastewater treatment facility. Previous studies are unclear whether phased digestion systems benefit from phase separation or temperature variation. By operating both stages of the acid/gas system at mesophilic temperatures and operating the thermophilic digester at a 10 day SRT to discourage phase separation, the effects of phase separation were observed independent of temperature variation. Relative performance was based on a comparison of volatile solids reduction (VSR), methane production, and residual biological activity (RBA), as well as effluent cations and volatile fatty acids. The temperature-phased digestion system performed best, having significantly higher VSR (61%) and having the lowest RBA of the three systems. All systems had close to the theoretical specific methane yield of 0.350 L CH_4/g COD destroyed at standard temperature and pressure (STP). However, the calculated methane production rate for the thermophilic digester (0.55 L CH_4/ L·day at STP) was highest of all digesters. The results of this study demonstrate that temperature variation enhanced performance more than phase-separation, though propionic acid data suggest that the acid/gas and temperature phased systems were not optimally configured.

Keywords

anaerobic, digestion, thermophilic, mesophilic, temperature, phased, primary sludge, waste activated sludge, biosolids

Introduction

Anaerobic digestion is a common method used to stabilize municipal wastewater treatment residuals and phased anaerobic digestion is a recent technology for digestion facilities. Metcalf and Eddy (2003) list four digestion phasing configurations: staged mesophilic digestion, temperature-phased digestion, acid/gas phased digestion, and staged thermophilic digestion. Often the words "phasing" and "staging" are used interchangeably in the literature regarding multiple reactor digestion systems. For clarity, phased anaerobic digestion is defined as a digestion system having two or more tanks, each with exclusive operating conditions that support unique biomass populations. Unique biomass populations may be acid-forming, methane-forming, thermophilic, or mesophilic organism populations. Operational parameters manipulated in these systems include solids retention time (SRT) and temperature.

Acid/Gas Phased Digestion

Drawing on the growing knowledge of anaerobic microorganism metabolisms, Pohland and Ghosh (1971) first proposed acid/gas phased digestion. In acid/gas phased digestion, operators vary the SRT to kinetically select for either acid-forming or methane-forming microorganisms. Methane- forming microorganisms, having a slow growth rate, are washed out of a digester if the SRT is low enough. The low SRT and high organic loading causes an accumulation of organic acid intermediates in the first digester. The digester pH drops, creating conditions favorable for the growth of acid-formers, who have an optimum growth rate at around pH 6 (Dichtl, 1997). Accordingly, the first digester in acid/gas-phased systems is operated at a low SRT (12 hours-1.5 days) to promote the growth of acid-forming micro-organisms, while the following digester has a high SRT (≥18 days) to allow for the establishment of a methane forming biomass. Studies suggest improved performance of acid/gas phased digestion versus single stage digestion (Ghosh, 1985) as measured by volatile solids reduction. Furthermore, several full-scale installations are in operation in the United States with proven success (Wilson and Dichtl, 2000).

Temperature Phased Digestion

In temperature-phased digestion, the temperature is varied between digesters to select for mesophilic or thermophilic microorganisms. Digesters are usually operated from 30-38° C for mesophilic conditions and 50-60°C for thermophilic. Thermophilic digestion is of interest to regulators and the wastewater industry due to its pathogen reducing potential. In addition to the pathogen reducing potential of thermophilic digestion, other reported benefits include increased volatile solids VSR and improved dewatering (Parkin and Owen, 1986). Thermophilic digestion is thought to enhance digestion due to increased biochemical reaction rates of thermophilic microorganisms (Buhr and Andrews, 1977). Faster biochemical reactions allow for smaller tank volumes for thermophilic digesters, thereby decreasing the footprint for construction (Dichtl, 1997). However, thermophilic digestion has a reputation for instability caused by fluctuations in the pH and odor problems caused by high levels of volatile fatty acids (VFA) in the effluent (WEF, 1987).

Temperature-phased digestion takes advantage of the aforementioned benefits of thermophilic digestion, while utilizing a second mesophilic digester to increase the stability of the thermophilic digester and decrease the odor potential of thermophilically digested biosolids (Han and Dague, 1997). The temperature-phased anaerobic digestion process, or TPAD, received a U.S. patent in 1996 (Dague et al., 1996). This process is very similar to the European equivalent anaerobic stabilization thermophilic/mesophilic (ASTM) process (Oles et al., 1997). Though the TPAD patent application included a broad range of operational temperatures and digester configurations, a typical TPAD configuration is a thermophilic digester operated at 55°C with an SRT of 3-5 days, followed by a mesophilic digester operated at 35°C operated at 10 or more days (Metcalf and Eddy, 2003).

It seems that for TPAD systems utilizing a first-stage thermophilic digester, the phasing operation that Pohland and Ghosh proposed is not optimized because it is difficult to achieve complete phase-separation at thermophilic temperatures. Research has shown that thermophilic digesters do not achieve optimal pH conditions to solely support acid-formers at SRT's less than 3 days. Accordingly, they are operated at

retention periods between 3 and 5 days to achieve a balance between the acid-formers and methane-formers (Dichtl, 1997).

Objectives

When comparing temperature-phased and acid-gas phased digestion, it is unclear whether the improved performance of these phased digestion systems is due to phase separation or to temperature variation. This study compares the performance of temperature phased thermophilic/mesophilic digestion (TPTM), acid/gas-phased mesophilic/mesophilic (AGMM) digestion, and single stage mesophilic digestion (SSM). The SSM digester is used as a control for comparison. The SRT of the 1st stage thermophilic digester in the temperature-phased system is sufficiently long to prevent acid-phase development. In this manner, a comparison can be made between the effects of varying temperature without the influence of phase development. It was part of a larger study to aid designers of the Blue Plains anaerobic digestion facility, scheduled for completion in 2008.

Methods and materials

The digesters selected for this study all had a total system SRT of 20 days. The SRT and temperature regime was selected to operate the multiple digester systems as an acid-gas phased system and a temperature-phased system (Table 1). The SRT of the digesters was maintained by operating at a constant volume through a mass balance approach, with feed volume equal to waste volume (Figure 1). The digesters were in a controlled temperature room set at 36.5 °C, keeping the digester temperature at 35±1 °C. Thermophilic temperatures were achieved by circulating 65 °C water in flexible vinyl tubing that encircled the thermophilic digesters. This kept the thermophilic temperature at 55±1 °C.

Vessels used for digestion were conical shaped tanks commonly used for home beer making. Two models were used: A 6.5 gallon stainless steel Fermenator™ manufactured by Blinchmann Engineering was used for the 1st stage thermophilic, 2nd stage mesophilic, and single stage mesophilic reactors. A 6.5 gallon plastic Affordable Conical Fermenter manufactured by Hobby Beverage Equipment Company was used for

the gas phase digester. Both of these models were available from Grape and Granary in Akron, OH. Silicone was used to seal the lids on these digesters and a large rubber stopper was substituted for the standard lid of the Affordable Conical Fermenter. Due to the short SRT and small operating volume of the acid phase digester, a six-liter low – profile spinner flask (Bellco Glass Inc., Vineland, NJ) was used instead of the larger volume conical vessels.

Mixing was achieved by circulating gas from the headspace of each digester and injecting it into a valve at the bottom of the digester (Figure 2). . The relatively deep cylindrical shape, combined with steeply sloped conical bottom of the digesters was thought to enhance mixing efficiency in a similar manner to egg-shaped digesters. In the case of the acid digester, gas was injected into a manifold that distributed the gas across the bottom of the vessel. The degree of mixing could be increased or decreased using 6-600 RPM variable speed peristaltic pumps that circulated the gas (Cole-Parmer, Vernon Hills, Illinois). Normally, the pumps were set at 40% of their maximum speed. This corresponds to approximately 0.7 L/minute with the Cole-Parmer "L/S-18" tubing used on the pump heads. At least five minutes before wasting and feeding, the gas flow rate was increased to 1.4 L/minute to ensure that waste samples were representative of the digester contents. The flow rate was maintained at 1.4 L/minute for about 10 minutes after feeding to disperse the feed.

Gas from each digester accumulated in Tedlar bags (Fisher Scientific, Hampton, NH) attached to the digester's collection/recirculation system (Figure 2). The gas flow rate was calculated by measuring the volume of gas in the bags and dividing by the time between measurements. Large volume Tedlar bags were used to prevent the systems from becoming pressurized. Gas composition samples were obtained by transferring one liter of gas from the large bags to smaller bags that had syringe-sampling ports. The thermophilic digester required a water trap to capture about 50 milliliters per day of moisture that condensed in the gas lines and it was put back into the digester every other day.

The digesters were started using thickened waste activated sludge from the Blacksburg-VPI Sanitation Authority, Lower Stroubles Creek WWTP. Previous studies

showed favorable results of starting thermophilic and mesophilic digesters with waste activated sludge (Kim and Speece, 2002). Waste activated sludge equal to one half of the operating volume of each digester sat un-mixed in the digesters for about 10 days, and then feed was added in 0.5 liter increments each day until the final operating volume was achieved. Upon reaching operating volume, daily wasting and feeding operations commenced.

The feed was a blend of thickened primary and waste activated sludge from Blue Plains. The sludges were composited at Blue Plains over several days and shipped overnight to the laboratory twice per week. Upon arrival, they were mixed (1:1 volume ratio) and stored in a bulk tank in a walk-in cooler set at 4°C. Screening of both sludges to remove large particles occurred at the time of collection and additional screening occurred prior to feeding. The screen was a semi-spherical kitchen colander, with approximately 3-millimeter diameter holes distributed at about 2 per square centimeter. Total solids concentration of the feed was diluted to 3% at startup and was increased to ≥ 4% at 39 days into the experiment. Tap water was used to dilute the sludge, when necessary, to achieve the desired total solids concentration. Daily batch feeding and wasting was initially conducted until day 62 (3 SRTs) at which point a timer and pump system that cycled five times per day was used for semi-continuous feeding. Clogging in the feed line made it necessary to begin daily batch feeding and wasting at day 106 (~5 SRTs). At day 118 the total solids of the primary sludge from Blue Plains decreased to approximately 2.5% to 3%. Prior to this, the total solids of primary and waste activated sludge total solids was similar at around 5% to 6%. Therefore, from day 118 to the end of the study there was a higher mass proportion of waste activated sludge to primary sludge in the feed.

The following tests were used to compare the performance of the digesters:

- Total and volatile solids
- Gas production and composition
- COD
- pH
- Alkalinity

- Effluent volatile fatty acids (acetic, propionic, butyric)
- Soluble cations (Na^+, NH_4^+, K^+, Mg^{++}, Ca^{++})

Additional tests during the study included residual biological activity tests which were conducted once at the end of the study.

COD, pH, alkalinity, and solids testing were conducted according to Standard Methods (APHA, 1999).

Gas samples were analyzed with a Shimadzu model GC-14A gas chromatograph (Shimadzu Scientific Instruments, Columbia, MD) using the thermal conductivity detector (TCD). The column used was made from a 4 meter length of copper tubing with a 0.25 inch inner diameter. The column was coiled to fit in the GC-14A oven and packed with Haysep Q media (Supelco, Bellefonte, PA). Helium was the carrier gas, with column flow set at 17 mL/min.

In order to prepare samples for cation and effluent volatile fatty acid (VFA) analyses, a 500 mL sample of digester biosolids was centrifuged at 13,500 x *g* for 25 minutes. 50 mL of the supernatant was frozen for storage until the analyses were performed. Samples were usually frozen for no more than 7 days. At the time of analysis, the sample was thawed, centrifuged at 6,000 x *g* for 15 minutes, and then filtered through a 0.45 micron syringe filter. From this filtered sample, dilutions were made for cation testing and VFA testing.

Diluted VFA samples were acidified in their individual GC vial by adding concentrated phosphoric acid at a ratio of 1:10. The VFA samples were analyzed on a Hewlett Packard Model 5890 gas chromatograph using a flame ionization detector. A Nukol capillary column (Supelco) was used and samples were injected in splitless mode. The column flow gas was helium with a flow rate of 17 mL/min. Flow rates for the other gases used were as follows: Nitrogen – 13 mL/min, Hydrogen – 45 mL/min, Air – 450 mL/min.

Diluted cation samples were analyzed on a Dionex D-120 ion chromatograph utilizing a CS-12 column and conductivity detection with self-generating suppression of the eluent (Dionex Corp., Sunnyvale, CA). 20mM methanesulfonic acid was used for eluent at a flow rate of 1 mL/min.

The residual biological activity test (RBA) was a simplified modification of the additional digestion test method outlined by EPA (1993). It was conducted by incubating 100mL digester samples in serum vials at 36.5°C for at least 20 days. During the incubation period, the vials were periodically degassed and weighed. The weight lost from each vial was assumed to be from gasification of the VS in each sample. RBA was calculated by dividing the weight lost from each sample at the end of incubation by the weight of its VS content (analyzed prior to incubation) and is reported as percent VS lost.

Statistical analyses were conducted with SigmaStat 3.10 (SPSS Software Inc., Chicago, IL).

Results and Discussion

Operational notes: The digesters achieved stable operation within 3 SRTs. Stable operation was defined by steady pH, gas production, and volatile solids reduction (VSR). All the digesters, except for the acid digester, were within optimal pH and alkalinity ranges for normal anaerobic digestion (Parkin and Owen, 1986)(Table 2). The average pH in the acid phase digester was slightly higher than the optimal pH 6 for acid phase digestion and approximately 36% of the samples collected were between pH 5.45 and 6. While no foaming was observed in the other digesters, the acid digester experienced several episodes of foaming during the experiment.

Volatile solids reduction: The average VSR in the TPTM was 61% and differed significantly from the other two digesters. The AGMM and SSM reactors were not significantly different from each other at 54% and 52% VSR respectively (ANOVA on ranks: Dunn's Method, 95% confidence interval) (Table 3). The average VSR versus time shows that the TPTM system VSR was consistently higher than the other digesters during the study (Figure 3). Though not an objective of the study, it was also observed that the VSR was similar after switching from semi-continuous to batch feed mode (Figure 3). However, it is difficult to make a conclusion from this observation because at day 115 the total solids content of the primary sludge began to decrease. Since the feed was composed of primary and waste activated sludge mixed at equal volumes, the lower total solids content of the primary sludge means that the mass proportion of primary to waste activated sludge decreased. It seems that the decrease in VSR observed in Figure 3

may be due to the thinned primary sludge instead of the change in feed mode. While the VSR decreased for all reactors after a change to the primary sludge total solids (Figure 4), the SSM digester seemed to be effected the most at around a 26% decrease.

Variability in the data over time makes it is useful to compare several ranges of data (Figure 5). The 10th, 25th, median, 75th, and 90th percentiles are labeled on Figure 5 as reference. From these data, it can be seen that the 75th percentile of VSR for the AGMM and SSM systems was lower than the median for the TPTM system. This reflects the better VSR efficiency of the TPTM system over the time of observation, regardless of the feed mode. The residual biological activity test for each digestion system supported the higher VSR observed in the TPTM system (Figure 6) in that the TPTM system had the lowest RBA at 14. Similarly, the AGMM system had an RBA of 15% and the SSM had an RBA of 22%. A similar RBA for the AGMM and TPTM system was probably observed because the RBA was a batch test conducted on a single grab sample at the conclusion of the study.

Approximately 46% VSR occurred in the 1st thermophilic stage of the TPTM system, while 28% VSR occurred in the acid digester. The VSR was expected to be lower in the acid phase digester than in the thermophilic digester since the SRT of the thermophilic digester was 8 days longer. However, the better VSR from the TPTM system suggests that temperature differences played a more important role in VSR than phase separation. If hydrolysis was rate limiting for this feed then it might be that the thermophilic temperature enhanced hydrolysis better than phase separation and increased the VSR. On the other hand, complete phase separation was not always achieved in the acid digester as suggested by periods of pH higher than 6.0 and some methane was found in the biogas of the acid phase digester. An acid phase digester operated at an SRT of 1 to 1.5 days would be desirable for better comparison between AGMM and TPTM systems.

Gas production and composition: The 1st stage thermophilic digester of the TPTM system had significantly higher daily biogas production (18.9 L/day at STP) than the other digester at (Table 4)(ANOVA on ranks: Dunn's method, 95% confidence interval). However, the methane biogas content was highest in the gas phase digester of

the AGMM system at 72%, though the statistical difference was not evaluated (Table 4). The acid phase digester had an average of 30% methane in its biogas and was highly variable with a standard deviation of 15%. It was observed that the mixing in the acid phase digester was not always effective. Multiple factors, including high loading rates due to low SRT, foaming, clogging of the gas distribution manifold, and digester shape contributed to the mixing problem.

The 2nd stage mesophilic digester of the TPTM system had low daily biogas production at around 0.3 L/day, as compared to the biogas production in the other digesters that ranged from 5 to 19 L/day. Two explanations are likely: An undetected gas leak may have lowered observed daily production or non-optimal conditions existed in the digester.

Normalized methane production was slightly lower than the theoretical COD equivalence of methane for all digestion systems (Figure 7). This is likely explained by cell yield, which is not accounted for in the theoretical value.

Effluent VFAs: The effluent VFAs (C2-C4) were lowest in the SSM system (0.4 g/L) and highest in the acid digester at around 3.7 g/L as acetic acid (Figure 8). High VFA and low pH levels in the acid phase digester reflected the activity of acid formers. Interestingly, the average propionic acid concentration was higher than the average acetate concentration in the gas phase and 1st stage thermophilic digesters (Figure 9). The reason for the propionic acid build-up in these digesters is unknown, but propionic acid is known to be metabolized within a narrow range of hydrogen partial pressure. Its metabolism is thus dependent on digester hydrogen concentration, which in turn is dependent on healthy syntrophy between hydrogen producing and hydrogen consuming microorganisms. Propionic acid build-up in these digesters may have been indicative of non-optimal process biochemistry.

Research has shown that when thermophilic reactors are operated at higher organic loading rates and lower SRT, propionic acid concentration becomes lower than other acid intermediates (Dicthl, 1997). For this reason, a lower SRT in the thermophilic digester may have resulted in better performance overall in the TPTM system. Other studies have demonstrated that non-mixed digesters (both thermophilic and mesophilic)

produce less effluent volatile fatty acids (including propionic) than well-mixed ones, possibly due to closer proximity of hydrogen utilizing methanogens with hydrogen producing acetogens (Kim et al., 2002)(Stroot et al., 2002)(McMahon et al., 2002). These syntrophic interactions may have been improved by operating the 1st stage thermophilic digester and the gas-phase digester with intermittent instead of continuous mixing, thereby improving and the performance of the AGMM and TPTM systems.

Cations and ammonium: Ammonium was highest in the 2nd stage mesophilic digester of the TPTM system at 1.05 g/L (Table 5). However, the only significant difference was between the 2nd stage mesophilic digester and the acid phase digester (ANOVA on ranks: Dunn's method, 95% confidence interval). Because the TPTM system had higher VSR, it is likely that it degraded more protein and caused higher effluent ammonium in the 2nd stage mesophilic digester. Conversely, since the acid phase digester had the lowest VSR, it is likely that it had the lowest protein degradation and thus the lowest effluent ammonium.

Calcium was significantly higher in the acid phase digester and all other digesters except the 1st stage thermophilic (ANOVA on ranks: Dunn's method, 95% confidence interval). Conditions in the acid digester, low pH and high CO_2 in the headspace, favored the higher soluble calcium concentration versus the other digesters.

Discussion: The TPTM system seemed to have an advantage over the AGMM and SSM system during this study as evidenced by higher VSR, gas production, and effluent ammonium, and lower RBA. One possible explanation is that the advantage was due to the kinetics of digester configuration. Perhaps the TPTM system behaved more like a plug flow reactor due to its configuration, while the AGMM and SSM system were more similar to complete mix reactors. A tracer study would be useful in characterizing the reactor configuration for future studies. The other possible explanation for the TPTM system advantage is that the temperature variation was more effective than phase separation. It is possible that the feed to these digesters was more amenable to thermophilic treatment than to mesophilic acid phase digestion, perhaps due to better hydrolysis rates at thermophilic temperatures.

Despite the TPTM advantage, performance did not seem optimized in either the TPTM or the AGMM systems. The acid-phase digester of the AGMM system experienced difficulties that may have decreased performance of the system. At times the acid phase digester was higher than the optimal pH 6 and experienced several foaming episodes. In addition, an average of 30% methane was detected in the headspace of the acid phase digester. On the other hand, the TPTM system did not seem optimized as evidenced by a higher proportion of propionic acid than the other acid intermediates in the 1st stage thermophilic digester and low biogas production in the 2nd stage mesophilic digester. Better mixing and a lower SRT in the acid-phase digester to enhance hydrolysis and acidogenic reactions, and intermittent mixing in the gas phased digester to maximize syntrophic interaction may have possibly improved the performance of the AGMM system. A lower SRT in the thermophilic digester to minimize propionic acid and higher SRT in the mesophilic digester to enhance methanogenesis, as well as intermittent mixing of both digesters to minimize disruption of syntrophic interactions, may have optimized the performance of the TPTM system.

Despite non-optimized conditions, the TPTM system did provide the best performance of the digesters studied. This may be due to the advantages of temperature variation and the unique biomass populations that thrive in each digester of the system. Additionally, thermophilic temperatures may have enhanced hydrolysis of the feed sludge. Future studies would benefit from comparing the AGMM and TPTM system at varying SRT and OLR conditions, as well as different mixing regimes. Additionally, it would be useful to operate an AGMM system at the same SRT distribution as the TPTM system in this study and keep the pH near 6.0 in the first stage digester through chemical addition. In this way, the only variable between the two systems would be an acid phase digester versus a thermophilic phase digester. Lastly, microbiological investigations would be useful to determine differences in biomass populations in each type of system to advance the understanding of anaerobic digestion performance issues.

Conclusions

Temperature phased digestion was compared to acid gas phased digestion in this study, with a single-stage mesophilic digester operated for comparison. The SRT of the

temperature phased digestion system was set to prevent phase separation so that temperature effects could be evaluated independently from phase separation. The TPTM system performed best during this study as supported by the following observations:

- The TPTM system had the highest average volatile solids reduction of all the systems studied at close to 61%. AGMM was second best at 54%, followed by SSM at 52%.
- The 1st stage thermophilic digester of the TPTM system had the highest biogas production at 18.9L/day (at STP).
- Total volatile fatty acid levels were highest in the acid phase digester, though propionic acid levels were at times higher in the gas phase digester than in the acid phase digester.
- Propionic acid was higher than acetic acid in both the gas-phase and 1st stage thermophilic digester.
- Ammonium was highest in the 2nd stage mesophilic digester of the TPTM system, suggesting higher protein degradation.

The results of this study indicate that temperature phased digestion may be a suitable candidate for an anaerobic digestion process at the Blue Plains anaerobic digestion facility. Continued studies for Blue Plains in this laboratory have focused on comparing temperature phased digestion to single stage mesophilic digestion and optimizing SRT for the temperature phased system.

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Table 1 - Operational parameters for digestion systems evaluated during the study. (Back)

Digester	Temperature (°C)	SRT (days)	Volume (L)	Acronym
Acid Phase	35	2	4	AGMM[a]
Gas Phase	35	18	18	
1st Stage Thermophilic	55	10	20	TPTM[b]
2nd Stage Mesophilic	35	10	10	
Single Stage Mesophilic	35	20	20	SSM[c]

a – Acid gas mesophilic mesophilic
b – Temperature phased thermophilic mesophilic
c – Single stage mesophilic

Table 2 – Digester pH and alkalinity during the study. **(Back)**

Digester	Avg Alk*	*s.d.*	Avg pH	*s.d*
SSM	4524	*529*	7.54	*0.22*
Acid	2462	*185*	6.12	*0.43*
Gas	4951	*851*	7.65	*0.21*
Thermo	4551	*715*	7.70	*0.27*
Meso	5160	*636*	7.74	*0.17*
Optimal	1000-5000		6.5-7.5	

SSM – Single stage mesophilic
***Alk – Alkalinity (mg/L as $CaCO_3$)**

Table 3 - Statistical analysis results of volatile solids reduction data. (Back)

ANOVA on ranks (Dunn's Method)			
Comparison	**Diff of Ranks**	**Q**	**P<0.05**
TPTM vs. SSM	37.544	4.251	Yes
TPTM vs. AGMM	33.294	3.92	Yes
AGMM vs. SSM	4.25	0.498	No

AGMM – Acid gas mesophilic mesophilic
TPTM – Temperature phased thermophilic mesophilic
SSM – Single stage mesophilic

Table 4– Summary of gas testing data. (Back)

Digester	AVG Gas Flow	*s.d.*	AVG CO_2	*s.d.*	AVG CH_4	*s.d.*	$MPR_{calc.}$
	L/day		%		%		(L CH_4/L·d)
Acid	4.6	*2.0*	*57*	*11*	*30*	*15*	0.34
Gas	12.5	*2.1*	*36*	*6*	*72*	*4*	0.50
1st Stage Thermophilic	18.9	*5.3*	*42*	*10*	*59*	*4*	0.55
2nd Stage Mesophilic	0.3	*0.2*	*31*	*8*	*53*	*9*	0.02
Single Stage Mesophilic	11.9	*1.3*	*35*	*8*	*66*	*10*	0.39

Table 5 – Digester cation concentrations during the study. (Back)

Digester	Na Avg	*s.d.*	NH_4-N Avg	*s.d.*	K Avg	*s.d.*	Ca Avg	*s.d.*	Mg Avg	*s.d.*
	(mg/L)		(mg/L)		(mg/L)		(mg/L)		(mg/L)	
SSM	37.0	*10.6*	956.3	*100.8*	100.4	*25.8*	113.2	*47.1*	42.8	*13.8*
1st Stage Thermo	34.8	*11.6*	926.8	*236.0*	92.4	*30.9*	136.2	*23.5*	38.9	*11.9*
2nd Stage Meso	36.1	*13.6*	1049.9	*245.7*	90.1	*33.2*	110.0	*42.6*	37.8	*17.0*
Acid	40.2	*7.0*	816.2	*51.8*	105.5	*16.2*	231.5	*61.9*	52.2	*11.9*
Gas	50.0	*46.0*	984.6	*125.2*	147.5	*119.9*	121.2	*31.0*	55.9	*24.0*

SSM – single stage mesophilic

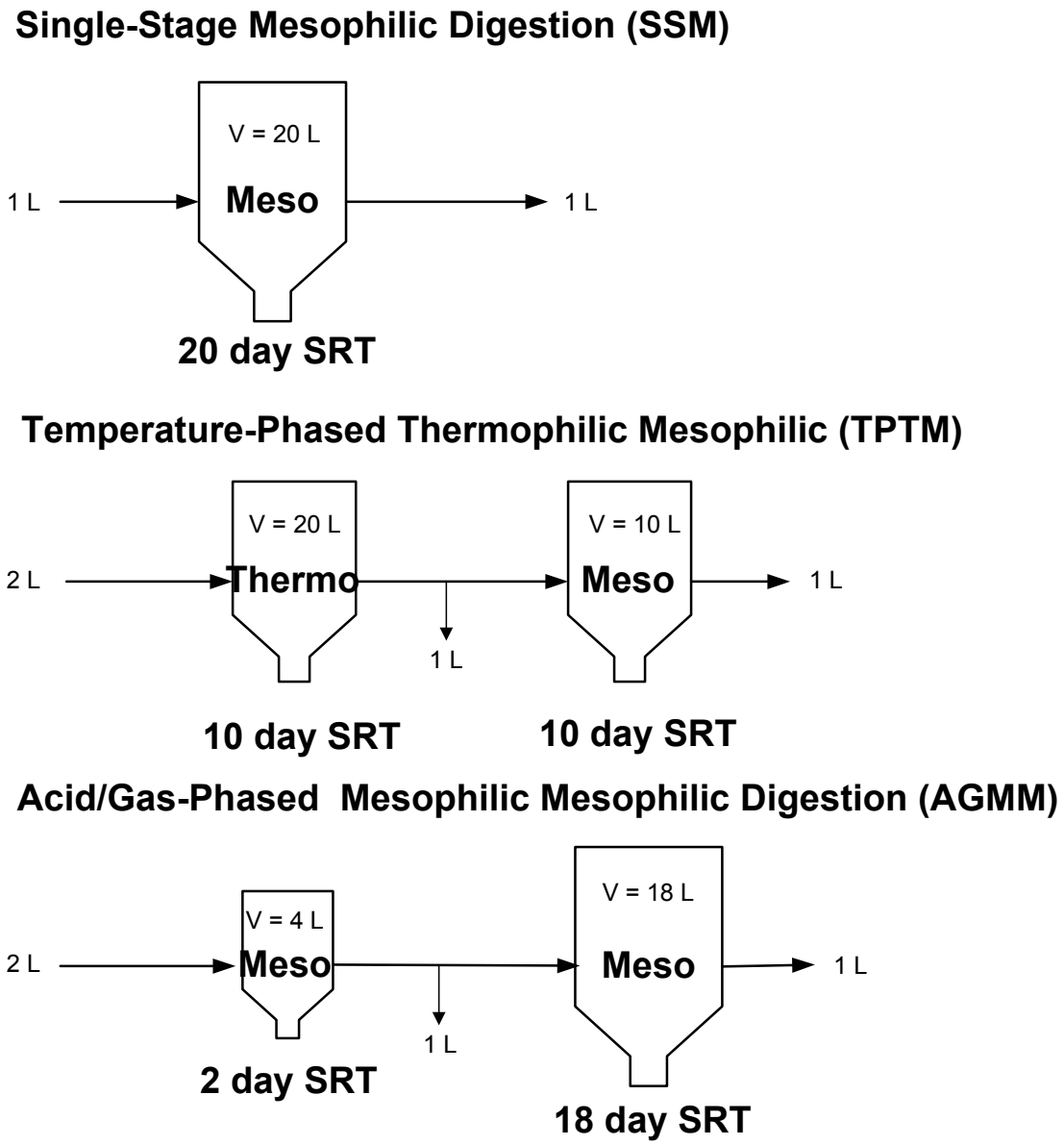

Figure 1- Flow diagram for the digestion systems. (Back)

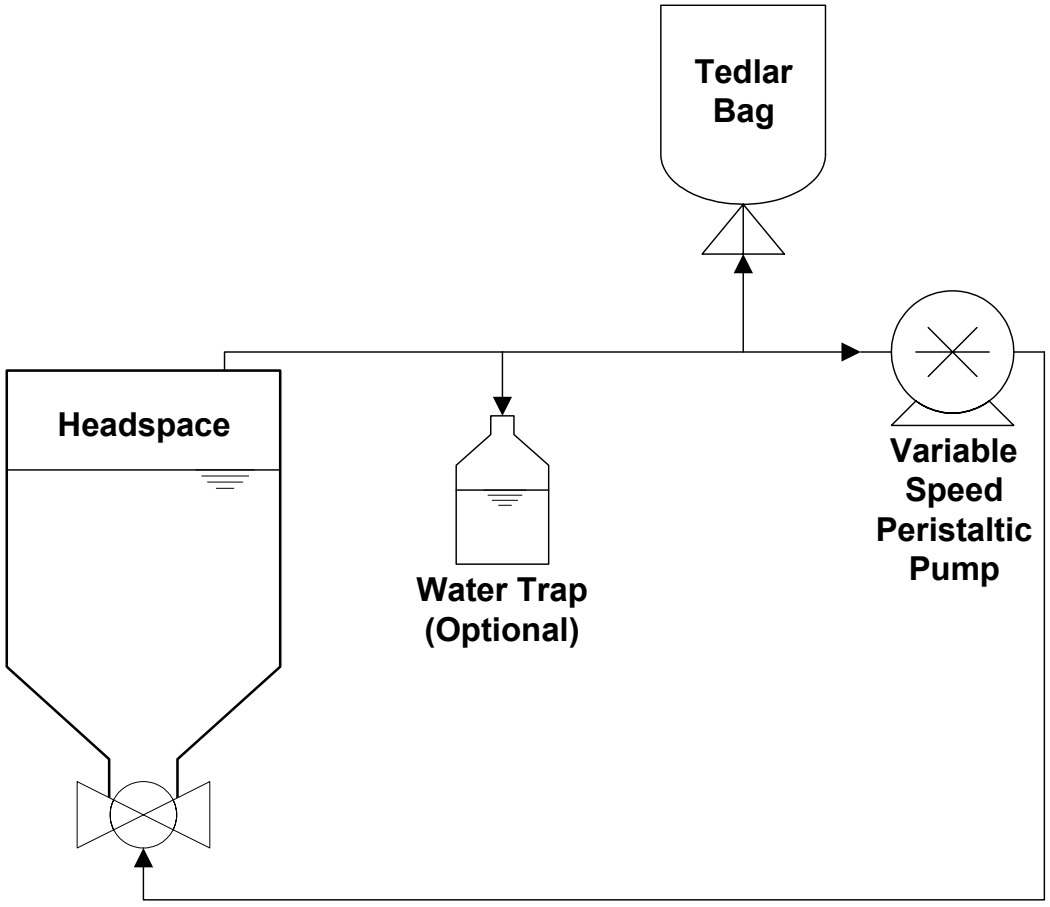

Figure 2 – Gas recirculation diagram for experimental setup. Water trap was utilized on the thermophilic reactor to prevent condensation from accumulating in the gas lines. **(Back)**

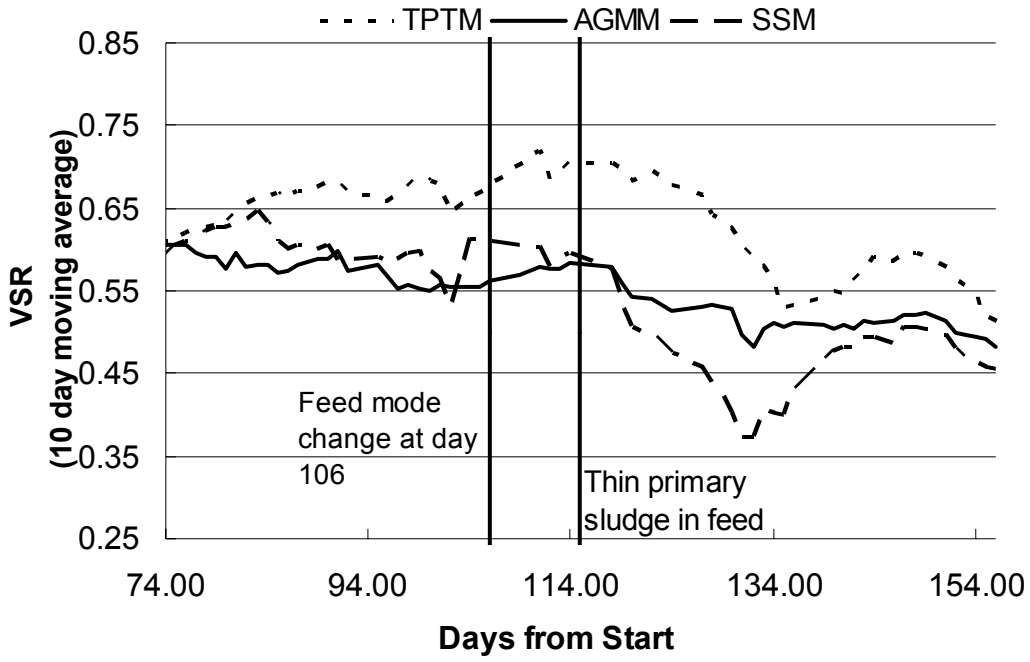

Figure 3 –Volatile solids reduction (10 day moving average) with time. Feed mode was changed from semi-continuous to batch at day 106 and primary sludge total solids decreased at day 115. **(Back)**
AGMM – Acid gas mesophilic mesophilic
TPTM – Temperature phased thermophilic mesophilic
SSM – Single stage mesophilic

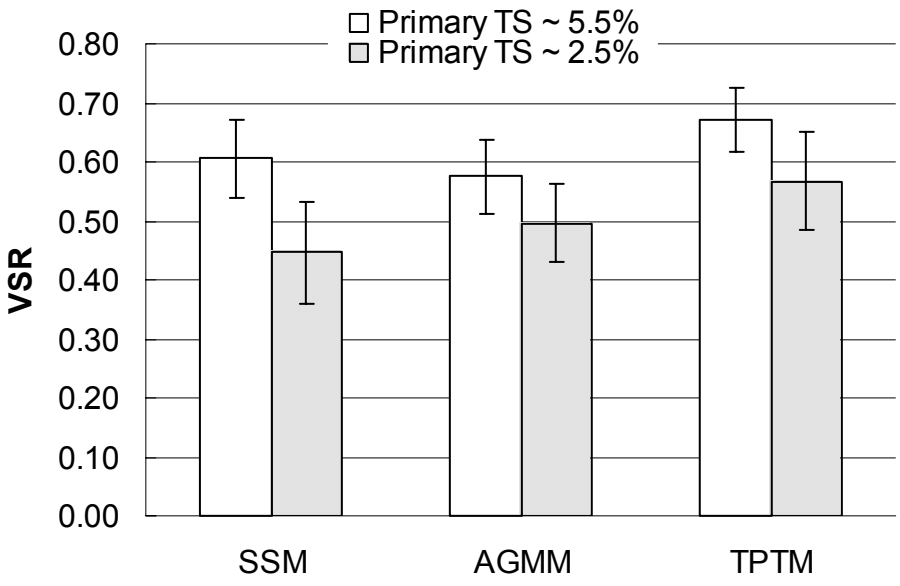

Figure 4 – Volatile solids reduction before and after change in primary sludge total solids (TS). High/low bars represent standard deviation. **(Back)**
SSM – Single stage mesophilic
AGMM – Acid gas mesophilic mesophilic
TPTM – Temperature phased thermophilic mesophilic

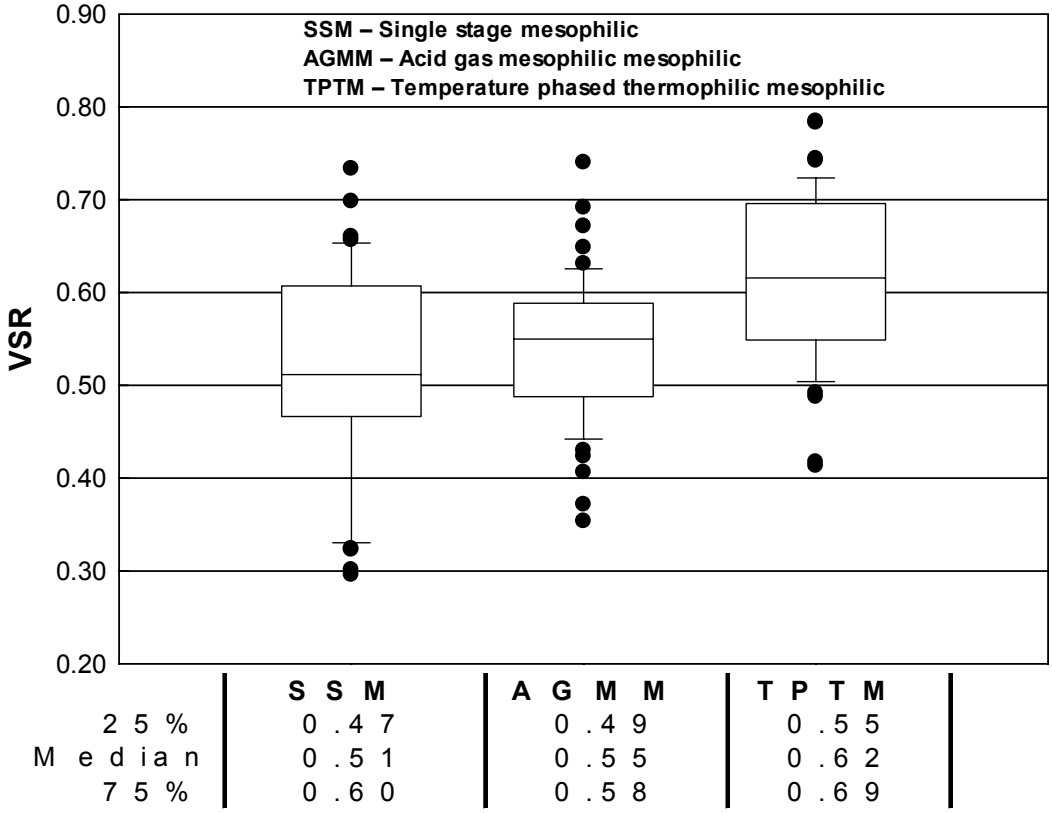

Figure 5– Volatile solids reduction after 74 days. High/low bars represent the 10th and 90th percentiles and points outside this are considered outliers. **(Back)**

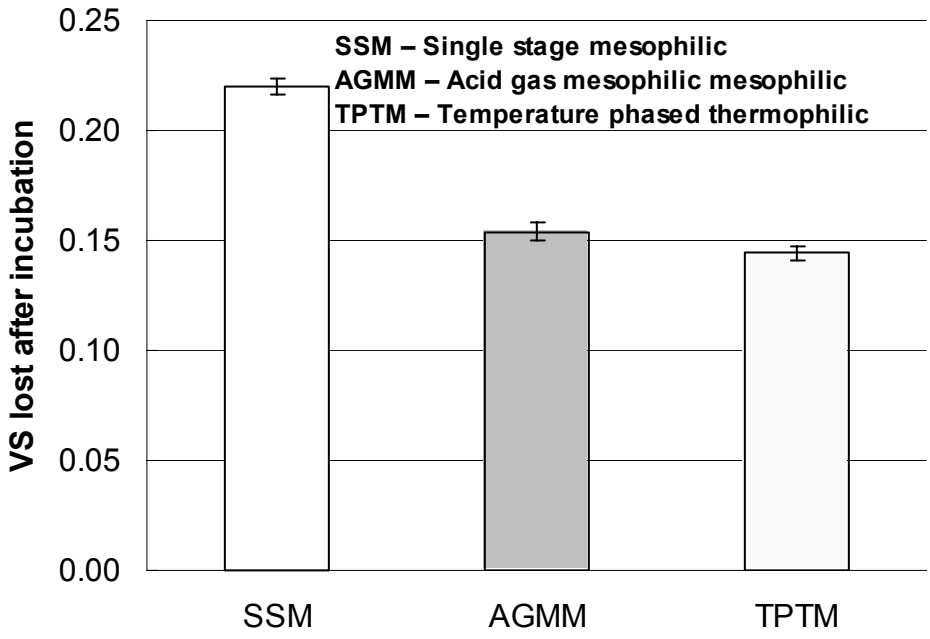

Figure 6 – Residual biological activity test results. Grab samples were collected on the last day of the experiment (day 160). **(Back)**

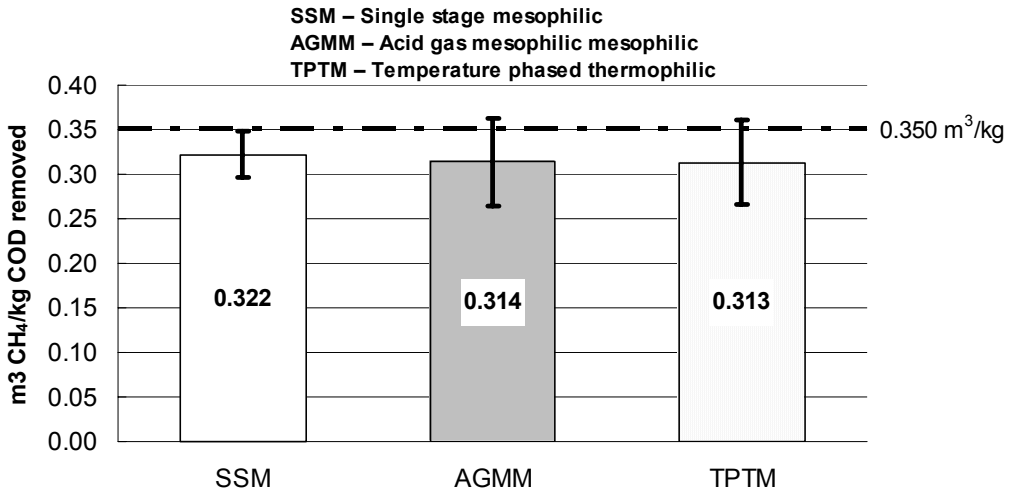

Figure 7 - Normalized methane production for each digester system at STP. Theoretical methane production is noted for comparison. **(Back)**

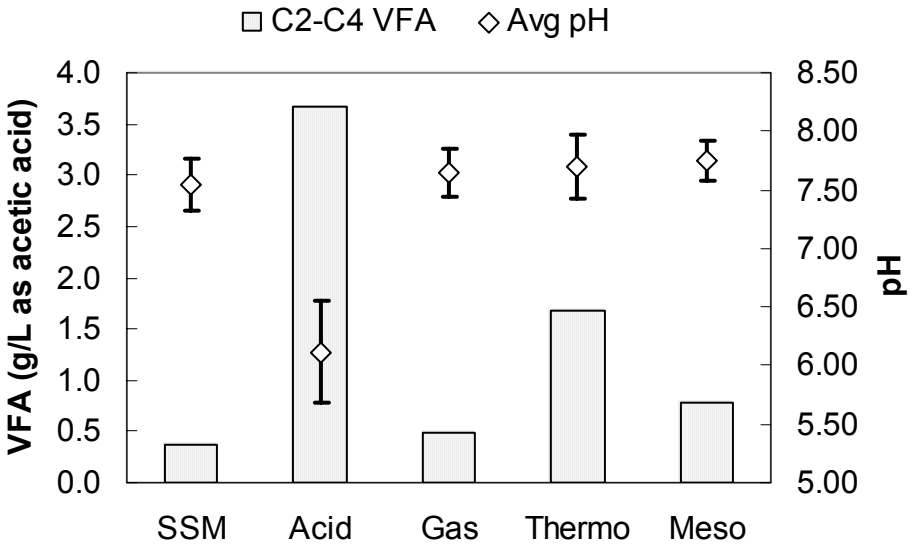

Figure 8 – Effluent volatile fatty acids (VFA) and reactor pH. High/Low bars represent one standard deviation for pH data. **(Back)**
SSM – Single stage mesophilic.

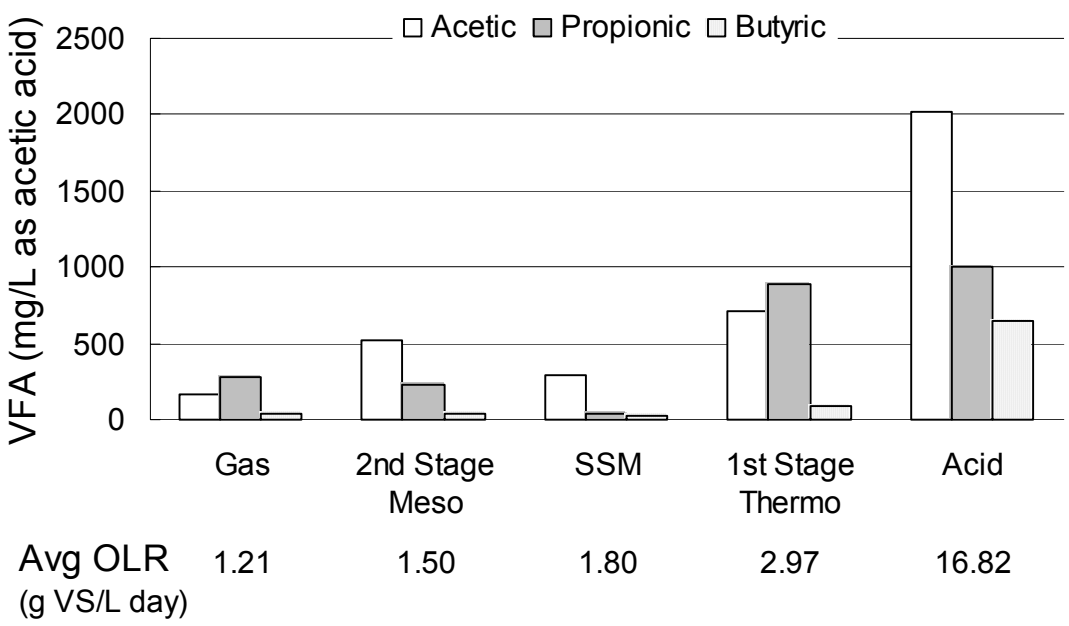

Figure 9 – Distribution of volatile fatty acids (VFA) and organic loading rate (OLR). **(Back)**

SSM – Single stage mesophilic

Manuscript 2

A Comparative Study of Temperature-Phased Digestion to Single Stage Thermophilic and Mesophilic Digestion

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Abstract

Three bench scale anaerobic digestion systems, operating in parallel, treated a blend of primary and secondary residuals (at 4% total solids) from Blue Plains wastewater treatment plant (WWTP), Washington, D.C. The digestion systems were temperature-phased anaerobic digestion (TPAD), single stage thermophilic (SST) and single stage mesophilic (SSM) anaerobic digestion. Solids retention time (SRT) and organic loading rates (OLR) were changed between each of three study phases. The TPAD system demonstrated the best performance by destroying more volatile solids and having lower residual biological activity than the other digesters during each phase of the study. Maximum volatile solids reduction (VSR) was 67% by the TPAD system with a 15 day SRT (each stage at 7.5 days). The SSM digester had a VS reduction of 63%, which was 9% higher VSR than the SST digester when both were operated at 20 days SRT. This indicated that perhaps a fraction of the feed sludge was degraded only under mesophilic temperatures. The results of this study, combined with additional studies on odor production and dewatering, have demonstrated an advantage to TPAD digestion as a process for Blue Plains to implement in their anaerobic digestion facility that will be constructed by 2008.

Keywords

Thermophilic, temperature phased, mesophilic, staged, anaerobic, digestion, biosolids,

Introduction

Mesophilic digestion performed in a single digester is the most common method utilized for residuals stabilization in municipal wastewater treatment. In the past several decades, practitioners have looked to alternative digestion technologies to improve pathogen destruction and volatile solids reduction (VSR). Land application requirements

and public health concerns have lead to the development of technologies to reduce pathogens in digested biosolids. Rising transportation, disposal, and handling costs have driven the search for higher volatile solids reduction and better dewaterability.

Thermophilic digestion is one example of an alternative technology, though it is by no means a new process. The main interest in thermophilic digestion is due to its pathogen reducing potential that was documented at least 75 years ago (Rudolfs and Heulekian, 1930). Other cited advantages of thermophilic treatment over mesophilic treatment include higher reaction rates, better dewaterability, and increased volatile solids reduction (Buhr and Andrews, 1977).

While thermophilic digestion has demonstrated the capability for reducing pathogens to a point suitable for classification as Class A biosolids (i.e. pathogen levels below detectable limits), the EPA has not listed it as an alternative technology suitable for this purpose because of operational stability issues (Metcalf and Eddy, 2003). Fluctuating volatile fatty acid (VFA) levels, odorous effluent, and foaming problems have all been attributed to thermophilic digester operation (WEF, 1987). A better understanding of optimal operating conditions may one day minimize such problems. For example, Kim et al. (2002) showed that a non-mixed thermophilic reactor had VSR equal to a well mixed thermophilic reactor, but produced much less effluent propionic acid and total VFA.

A recently developed alternative digestion technology seeks to enhance the benefits of thermophilic digestion while minimizing its risks. This system is called temperature-phased anaerobic digestion (TPAD) in the U.S. (Dague et al., 1996) and the Anaerobic Stabilization Thermophilic/Mesophilic system (ASTM) in Europe (Oles et al., 1997). The U.S. patent application for the TPAD process lists a wide range of solids retention time (SRT) and temperature under which TPAD processes may be operated (Dague et al., 1996). Commonly, TPAD processes include a thermophilic reactor (3-5 day SRT) followed by a mesophilic digester (>18 day SRT) (Metcalf and Eddy, 2003). These systems benefit from both temperature variation and partial phase separation.

Phased-digestion refers to the separation of acid-formers from methane-formers through environmental selection (Massey and Pohland, 1978). In practice, this is accomplished by adjusting digester pH through chemical control or kinetically by

lowering SRT to wash out methane formers. Pohland and Ghosh (1971) developed the concept of kinetic phase separation and Ghosh's subsequent research cited advantages of phase separation, such as enhanced volatile solids reduction, gasification, and stability (Ghosh, 1987). Other research has suggested the costs may outweigh the benefits to phase separation (Bhattacharya et al., 1996). However, it has been applied successfully in several full-scale operations (Wilson and Dichtl, 2000). Two phased anaerobic digestion (2PAD) is a variation of acid gas phased anaerobic digestion and includes a thermophilic digester as the first acidogenic digester, where the pH is maintained in acidophilic ranges through chemical control (Huyard et al., 2000). The thermophilic temperatures allow the 2PAD process to destroy pathogens to meet Class A biosolids requirements.

Some claim that true phase separation cannot occur in thermophilic digestion because thermophilic temperatures preclude the development of a sole acid-forming stage (Dichtl, 1997). Because of this, Dichtl suggests that a thermophilic digester in the TPAD system should be operated between 3 and 5 days, which achieves an adequate balance between acid-formers and methane-formers and minimizes propionic acid accumulation. Research conducted in this laboratory showed that a temperature phased system with a thermophilic followed by mesophilic configuration (both reactors at 10 day SRT) destroyed significantly more volatile solids than an acid-gas phased system with a 2 day SRT acid digester and an 18 day SRT gas digester (both stages mesophilic)(Inman, 2004). The long SRT of the thermophilic reactor prevented phase-separation and indicates that thermophilic temperatures may be more important than phase-separation for improved performance in temperature-phased digestion of wastewater residuals. However, a short SRT in the first stage thermophilic digester is economically desirable due to a smaller operating volume.

Many researchers have demonstrated advantages to TPAD processes. Han and Dague (1997) demonstrated 18% higher volatile solids reduction and methane production from a TPAD process versus a single stage mesophilic digester across a range of SRTs from 10 to 15 days. Yet improved VSR may come at the cost of poor dewatering. Bivins and Novak (2001) observed poor biosolids dewatering characteristics in a bench-scale TPAD system: Dewaterability, as measured by capillary suction time and optimal

polymer dose, became worse when the 1st stage thermophilic reactor was increased from a detention time of 1.5 to 3 days. Nevertheless, class A biosolids production capability may outweigh the disadvantage of poor dewatering characteristics. Vandenburgh and Ellis (2002) showed a TPAD process capable of meeting Class A biosolids requirements across a range of solids loading conditions. The first stage thermophilic reactor in their study also tolerated high levels of un-ionized ammonia (326 mg/L), suggesting its suitability for treatment of high nitrogen wastes.

Objectives

The main objective of this study is to compare the performance of temperature-phased digestion (TPAD) and single stage mesophilic digestion (SSM) as measured by volatile solids reduction. Additionally, single stage thermophilic (SST) digestion is investigated since the TPAD system is configured for sampling the first stage thermophilic digester. Other tests used for comparison include methane production, residual biological activity, effluent volatile fatty acids and ammonium. The purpose of the study is to aid designers of an anaerobic digestion facility for Blue Plains WWTP, scheduled for completion in 2008. Temperature-phased digestion is a potential process configuration for this facility. The study was conducted in three testing phases, with each testing phase evaluating different operational conditions.

Methods and materials

Selected solids retention time (SRT) and temperature regimes were chosen to compare the performance of the digesters over a range of values (Table 1) and to calibrate design models for Blue Plains. All figures, graphs, and tables refer to the digesters by the acronyms listed on this table. The operating volume of the 1st stage thermophilic digester was larger than the 2nd stage mesophilic reactor. This was done so that excess waste was available for sampling (Figure 1). The SRT of the digesters was maintained by feeding and wasting equal volumes each day at around the same time (±1 hour).

Digesters were fed with a blend of thickened primary and waste activated sludge from the Blue Plains wastewater treatment plant in Washington, D.C. The sludges were

composited at Blue Plains over several days and shipped overnight bi-weekly. For the first phase of testing, the sludges were mixed at a 1:1 volume ratio and in the second and third phase they were mixed at a 1:1 weight ratio. Though the feed characteristics were very similar throughout each phase of the study (Table 2) it is important to note that the proportion of primary sludge to secondary sludge was unknown in the first study phase since they were mixed volumetrically. Also, the organic loading rate was not the same between the digesters in each phase since they were operated at different volumes (Table 3). Screening of both sludges to remove large particles occurred at the time of collection and additional screening occurred prior to feeding. The screen was a semi-spherical kitchen colander, with approximately 3-millimeter diameter holes distributed at about 2 per square centimeter. Total solids concentration of the feed was diluted to 3% at startup in the first phase and was increased to ≥ 4% at 39 days into the first phase experiment. Data presented for the first study phase only includes samples collected after the feed solids were increased. In subsequent testing phases the feed was maintained at around 4% throughout the experiments. Tap water was used to dilute the sludge, when necessary, to achieve the desired total solids concentration. Daily batch feeding and wasting was utilized in all three test phases.

The digesters were set up in a controlled temperature room set at 36.5 °C, keeping the digester temperature at 35±1 °C. Thermophilic temperatures were achieved by circulating 65 °C water in flexible vinyl tubing that encircled the thermophilic digesters. This kept the thermophilic temperature at 55±1 °C. Internal digester temperature was confirmed with a digital temperature gauge connected to thermocouples positioned inside the digesters. Since batch feeding was performed, digester temperature dropped once each day. This was most notable in the thermophilic digesters. During thermophilic digester feeding the temperature dropped to 45-48 °C and recovered in two to three hours.

Vessels used for digestion were conical shaped tanks commonly used for home beer making. Two models were used: A 6.5 gallon stainless steel Fermenator™ manufactured by Blinchmann Engineering and a 7 gallon plastic Mini-Conical manufactured by Hobby Beverage Equipment Company. Both of these models were

available from Grape and Granary in Akron, OH. To prevent digester biogas from escaping, the lids were sealed with silicone caulk.

Mixing was achieved by circulating gas from the headspace of each digester and injecting it into a valve at the bottom of the digester (Figure 2). The relatively deep cylindrical shape, combined with steeply sloped conical bottom of the digesters was thought to enhance mixing efficiency in a similar manner to egg-shaped digesters. The degree of mixing could be increased or decreased because 6-600 RPM variable speed peristaltic pumps circulated the gas (Cole-Parmer, Vernon Hills, Illinois). Normally, the pumps were set at 40% of their maximum speed. This corresponds to approximately 0.7 liters/minute with the Cole-Parmer L/S 18 tubing used on the pumps. At least five minutes before wasting and feeding, the gas flow rate was increased to 1.4 LPM to ensure that waste samples were representative of the digester contents. After feeding, the flow rate was maintained at 1.4 LPM for about 10 minutes to disperse the feed.

Gas from each digester accumulated in Tedlar bags (Fisher Scientific, Hampton, NH) attached to the digester's collection/recirculation system (Figure 2). The gas flow rate was calculated by measuring the volume of gas in the bags and dividing by the time between measurements. Large volume Tedlar bags were used to prevent the systems from becoming pressurized. Gas composition samples were obtained by transferring one liter of gas from the large bags to smaller bags that had syringe-sampling ports. The thermophilic digester required a water trap to capture about 50 milliliters per day of moisture that condensed in the gas lines and it was put back into the digester every other day.

The digesters in the first testing phase were started using thickened waste activated sludge from the Blacksburg-VPI Sanitation Authority, Lower Stroubles Creek WWTP. Previous studies showed favorable results of starting thermophilic and mesophilic digesters with waste activated sludge (Kim and Speece, 2002). Waste activated sludge equal to one half of the operating volume of each digester sat un-mixed in the digesters for about 10 days, and then feed was added in 0.5 liter increments each day until the final operating volume was achieved. Upon reaching operating volume, daily wasting and feeding operations commenced. Digesters in the second and third test

phases were seeded with the reactor contents from the previous testing phases, except for the 25 day SSM, which was started with mesophilically digested sludge from the Pepper's Ferry WWTP.

Tests conducted during the study included:

- Total and volatile solids
- Gas production and composition
- Total chemical oxygen demand (COD)
- pH
- Alkalinity
- Effluent volatile fatty acids (acetic, propionic, and butyric/isobutyric)
- Soluble cations (Na^+, NH_4^+, K^+, Mg^{++}, Ca^{++})

Additional tests during the study included residual biological activity tests which were conducted once at the end of the study.

COD, pH, alkalinity, and solids testing were conducted according to Standard Methods (APHA, 1999).

Gas samples were analyzed with a Shimadzu model GC-14A gas chromatograph (Shimadzu Scientific Instruments, Columbia, MD) using the thermal conductivity detector (TCD). The column used was made from a 6 ft x 0.25 inch copper tubing. The column was coiled to fit in the GC-14A oven and packed with Haysep Q media (Supelco, Bellefonte, PA). Helium was the carrier gas, with column flow set at 17 mL/min.

In order to prepare samples for cations and effluent volatile fatty acids (VFA) analysis, a 500 mL sample of digester biosolids was centrifuged at 13,500 x *g* for 25 minutes. Fifty mL of the supernatant was frozen for storage until the analyses were performed. Samples were usually frozen for no more than 7 days. At the time of analysis, the sample was thawed, centrifuged at 6,000 x *g* for 15 minutes, and then filtered through a 0.45 micron syringe filter (Fisher Scientific). From this filtered sample, dilutions were made for cation testing and VFA testing.

Diluted VFA samples were acidified in their individual GC vial by adding concentrated phosphoric acid at a ratio of 1:10. The VFA samples were analyzed on a

Hewlett Packard Model 5890 gas chromatograph using a flame ionization detector. A Nukol capillary column (Supelco) was used and samples were injected in splitless mode. The column flow gas was helium with a flow rate of 17 mL/min. Flow rates for the other gases used were as follows: Nitrogen – 13 mL/min, Hydrogen – 45 mL/min, Air – 450 mL/min.

Diluted cation samples were analyzed on a Dionex D-120 ion chromatograph utilizing a CS-12 column and conductivity detection with self-generating suppression of the eluent (Dionex Corp., Sunnyvale, CA). 20mM methanesulfonic acid was used for eluent at a flow rate of 1 mL/min.

The residual biological activity test (RBA) was a simplified modification of the additional digestion test method outlined by EPA (1993). It was conducted by incubating 100mL digester samples in serum vials at 36.5°C for at least 20 days. During the incubation period, the vials were periodically degassed and weighed. The weight lost from each vial was assumed to be from gasification of the VS in each sample. RBA was calculated by dividing the weight lost from each sample at the end of incubation by the weight of its VS content (analyzed prior to incubation) and is reported as percent VS lost.

Non-parametric statistical methods were utilized when comparing data. The Mann-Whitney rank sum method was used when comparing two groups. This is the non-parametric equivalent of the student's t-test. A one-way ANOVA on ranks with Dunn's method was used for pairwise comparison between three or more groups and is the non-parametric equivalent of the one-way ANOVA. These methods were necessary due to the data not always meeting normality or equal variance requirements of parametric statistical methods. Statistical analysis of results was conducted with SigmaStat 3.10 (SPSS Software Inc., Chicago, IL).

Results and discussion

***Digester pH and alkalinity**:* The digester pH and alkalinity conditions during the study are shown in Table 4. These are typical values for anaerobic digestion (Parkin and Owen, 1986).

Volatile solids reduction calculation method: VSR was calculated by the approximate mass balance method (Equation 1).

$$Equation 1: VSR = \frac{WasteVS - FeedVS}{FeedVS} \times 100$$

This equation assumes that daily flows are steady, reasonably uniform, and that digester volume and composition does not vary substantially on a daily basis (EPA, 1999). These were reasonable assumptions to apply to this experiment.

Volatile solids reduction: During the second and third testing phase, the TPAD system destroyed significantly more volatile solids compared to the other digesters in those phases (ANOVA on ranks: Dunn's method, 95% confidence interval). The highest VSR of 67% occurred in the TPAD7.5/7.5 system during the third testing phase (Figure 3). During the second phase, the TPAD5/10 system destroyed about 10% more VS than the SST20 system and around 7% more than the SSM15 digester. In the third phase, the TPAD7.5/7.5 system destroyed approximately 4% more VS than a SSM25 and 7% more than the SSM15 digester. However, in the first study phase, the SSM20 and TPAD10/10 systems were statistically equal (Mann-Whitney rank sum, 95% confidence interval). At all study phases, the TPAD digester was operated at a significantly higher OLR than the SSM digesters (ANOVA on ranks: Dunn's method, 95% confidence interval).

The VSR for the SST digesters in this study (48.5% to 53.6%) were lower than recently reported by Moen et al.(2003). However, the feed in this study had a lower average VS/TS ratio than the Moen et al. work (0.77 versus 0.83). The difference could also be from a higher proportion of waste activated sludge in the present study than in the Moen et al. study. There was no statistical difference between the VSR of any of the TPAD systems (ANOVA on ranks: Dunn's method, 95% confidence interval).

VSR for all reactors varied with SRT and OLR (Figure 4). Two data points from a SSM digester at 10 days SRT and a SST digester at 20 days SRT are included in Figure 4.. They are identified as solid points and were collected during a continuance of the overall study for Blue Plains that took place after the conclusion of study phase 3. The general trend observed was that VSR increased with increasing SRT and decreased with increasing OLR, except with the TPAD systems where VSR remained relatively constant

despite changes to SRT and OLR. A slight drop occurred in VSR for the SST10 digester and the TPAD10/10system. Since both of these were operated during the first phase, one possible reason for the drop is because the feed was not the same as for the second and third phases of the study because it was mixed volumetrically instead of by weight. This could have lowered the proportion of more readily degraded primary sludge relative to the waste activated sludge, thereby lowering the VSR for the digesters. Another possible reason is that the thermophilic biomass was not well acclimated in the first study phase. Waste activated sludge was used to start-up the thermophilic digester in phase 1 while subsequent thermophilic digesters were started with thermophilic seed from the previous study phase.

Figure 4 also suggests that the SSM digesters were more influenced by changes to SRT and OLR compared to the SST and TPAD digesters, as evidenced by a steeper profile across the range of OLR and SRT values. This observation agrees with research conducted in other laboratories (Vandenburgh and Ellis, 2002). However, the influence of OLR on VSR cannot be determined independently in the present study since SRT was not held constant.

A final point worth discussion from Figure 4 is the difference in performance between the single stage thermophilic versus single stage mesophilic digester at 20 days SRT. The SST20 digester had 9% lower VSR than the SSM20 digester. Though these data seem questionable, the data point included from the continuance of this study verifies the validity of the observation during this study. There are two possible reasons for this observation. One explanation is that free ammonia inhibited the thermophilic biomass at the 20 day SRT but not the mesophilic biomass. The proportion of free ammonia relative to total ammonia is shown by the relationship in equations 2 (Emerson et al, 1975) and 3 (Koster, 1986).

$$\text{Equation 2: } NH_3 = \frac{TNH_3}{1+10^{(pK_a - pH)}}$$

$$\text{Equation 3: } pK_a = 0.09018 + \frac{2729.92}{T}$$

Where:

NH_3 = free ammonia concentration (mg/L as N)
TNH_3 = total ammonia concentration (mg/L as N) = ($NH_3 + NH_4^+$)
K_a = equilibrium ionization constant; and
T = Temperature (K).

Since total ammonia was not analyzed, the ammonium concentration was substituted for the total ammonia concentration in these equations. Though using the ammonium concentration would likely under-estimate the true free ammonia concentration it still provides a useful comparison. The calculated free ammonia concentration in the SST digester (230 mg/L) was about 7 times higher than in the mesophilic digester (Table 5) and higher than the reported toxic levels for mesophilic biomass. Studies have indicated no problems when operating thermophilic digesters at levels as high as 326 mg/L free ammonia (Vandenburgh and Ellis, 2002) and an analysis of Moen et al.'s data (2003) shows that thermophilic and mesophilic digesters destroyed similar amounts of volatile solids even with a large difference in digester free ammonia concentration. Therefore, ammonia inhibition in the thermophilic digester may not be as plausible as the second speculated reason: the mesophilic biomass was able to degrade a portion of the feed not degraded by thermophilic biomass. This concept is depicted in Figure 5, where different portions of the feed are degraded differently by thermophilic and mesophilic biomass, though the net effect is that the mesophilic digester destroys more of the feed VS. It is well understood that anaerobic microorganisms in sludge digesters require certain substrates to perform their metabolism (Novaes, 1986). Studies have even shown how broad categories of microorganisms, such as the acidogens, may degrade certain substrates better than others(Fox and Pohland, 1994) What is not known is if particular species of anaerobic microorganisms are more efficient at degrading certain fractions of wastewater residuals than others, or how the biomass in digesters might adapt to degrade its food source. It is certain that many living organisms, plants and animals, have adapted to efficiently feed on specific food sources. By extending this logic to the present study, it is speculated that the mesophilic biomass was either better adapted to degrade or had a preference for a portion of the feed relative to the thermophilic biomass, as evidenced by the higher volatile solids destruction in the mesophilic digester.

Residual biological activity: The RBA values generally decreased with increasing SRT for the digesters and were lowest in the TPAD systems, which is in

agreement with the VSR data (Figure 6).. It is important to note that the RBA tests were conducted once at the end of each study phase and represented a single grab sample. Also, the RBA values are likely higher than what would be determined through the EPA additional digestion method (1999) due to loss of water vapor when venting the gas from the sample bottles.

***Digester volatile fatty acids**:* As expected, VFA was highest in the SST digesters during each testing phase (Table 6), with the highest average value of about 2.4 grams/L as acetic occurring in the SST5 digester. The proportion of propionic acid was also highest in the SST5 digester, which may indicate non-optimal conditions for anaerobic digestion, though this did not seem to effect the VSR performance of the TPAD5/10 system. It is notable that in all phases except the first, the TPAD effluent had considerably lower levels of VFA than the first stage thermophilic digester of the system, with higher proportions of acetic acid relative to propionic acid. In the TPAD10/10 system in the first study phase, the 2nd stage mesophilic effluent contained similar amounts of VFA to the SST10 effluent, suggesting that the mesophilic digester was not performing optimally. This may further explain the decreased VSR performance observed in the TPAD10/10 system.

***Biogas characteristics**:* The highest methane content was found in the SSM20 digester, at close to 66% (Table 7). The methane production rate, however, was highest in the thermophilic reactor during each test phase (Figure 7) because the thermophilic digesters had higher biogas production. Since OLR varied with each change in SRT during the study, it is difficult to evaluate the effects of SRT on specific methane yield without also considering the OLR. Figure 8 portrays the interactions between OLR, SRT, and specific methane yield. It is generally seen that as OLR increases, specific methane yield decreases, while SRT and specific methane yield increase with each other. However, the specific methane yield in the mesophilic digester remained fairly constant during each test phase, regardless of SRT and OLR.

***Ammonium ion concentration**::* The NH_4-N levels ranged from 0.93 g/L to 1.4 g/L during the study and were highest in the SST20 digester (Table 8). The SST20 digester was significantly higher than all digesters in the study, except for the SST5,

TPAD5/10, and TPAD7.5/7.5 (ANOVA on ranks: Dunn's method, 95% confidence interval). It is likely that the reason for higher ammonium concentration in the thermophilic digesters and the TPAD systems was due to higher protein degradation.

***Discussion**:* One disadvantage of the laboratory setup for this study is that SRT and OLR were changed together and that the OLR was higher for the TPAD system than the SSM digester. This makes comparing of the effect of SRT on digester performance difficult. Despite this drawback, it was observed that the TPAD digestion system destroyed significantly more VS than the SSM digesters(at significantly higher OLR) in the second and third phases of the study. The enhanced performance of the TPAD digester suggests that it is a suitable candidate for digestion processes at Blue Plains. Furthermore, odor tests conducted on these digesters have shown a distinct advantage to TPAD digested biosolids versus single stage mesophilic and single stage thermophilic.

Future comparative studies on TPAD digestion would benefit from operating at either a constant OLR, as in Han and Dague's work (1997), or by operating at a constant SRT with varying OLR, as in Vandenburgh and Ellis's study (2002). Both SRT and OLR have important implications in design and operation of TPAD digesters and such a study would help answer the question of how to optimize the performance of a TPAD system for Blue Plains.

Conclusions

The main study objective was to compare the performance of TPAD digestion to single stage mesophilic digestion as measured by VSR. To this end, three separate study phases were conducted with a TPAD system and a SSM digester operated at equal SRTs. Additionally, the performance of single stage thermophilic digestion was compared to TPAD and SSM digestion by sampling the first thermophilic stage of the TPAD system. Single stage thermophilic digestion had the highest observed specific methane yield (SST20 digester - 0.55 L CH_4 per gram VS destroyed) and the highest observed methane production rate (SST5 digester, at over 0.86 liter CH_4 per liter digester volume). Furthermore, the SST20 digester had the highest observed effluent ammonium at 1.4 g/L, suggesting high protein degradation. Nevertheless, it was concluded that thermophilic digestion alone was not as effective as mesophilic digestion at SRTs greater than 10 days

as supported by the data presented in Figure 4. However, TPAD digestion seemed to have an advantage to both SST and SSM digestion. It was concluded that the TPAD system demonstrated better performance throughout the study as supported by the following observations:

- At a 15 day SRT the TPAD system destroyed significantly more VS than the SSM digesters, though at a 20 day SRT there was no significant difference. Additionally, the TPAD system was operated at a significantly higher OLR than the SSM digesters at all SRTs.
- The TPAD7.5/7.5 digester in the third study phase destroyed the highest amount of VS during the entire study (67%) and destroyed significantly more VS (~4%) than a SSM digester operated at 25 days.
- The TPAD system was less influenced by increased OLR than the SSM and SST digesters.
- Residual biological activity tests indicated the most stable biosolids were produced by the TPAD10/10 and TPAD7.5/7.5 system.

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Table 1 - Operational parameters for digestion systems. (Back)

Test Phase	Digester	SRT (days)	Temperature (°C)	Volume (L)	Acronym
1	Single Stage Mesophilic	20	35	20	SSM20
	1st Stage Thermophilic	10	55	20	SST10
	2nd Stage Mesophilic	10	35	10	TPAD10/10
2	Single Stage Mesophilic	15	35	15	SSM15
	Single Stage Thermophilic	20	55	20	SST20
	1st Stage Thermophilic	5	55	15	SST5
	2nd Stage Mesophilic	10	35	10	TPAD5/10
3	Single Stage Mesophilic	15	35	15	SSM15
	Single Stage Mesophilic	25	35	25	SSM25
	1st Stage Thermophilic	7.5	55	26.25	SST7.5
	2nd Stage Mesophilic	7.5	35	11.25	TPAD7.5/7.5

SSM – Single stage mesophilic
SST – Single stage thermophilic
TPAD – Temperature phased anaerobic digestion

Table 2 – Feed characteristics for all study phases. (Back)

	Phase 1		Phase 2		Phase 3	
	Avg	***s.d.***	**Avg**	***s.d.***	**Avg**	***s.d.***
TS (%)	3.9	0.4	4.0	0.4	4.1	0.3
VS (%)	2.9	0.3	3.2	0.4	3.2	0.3
FS (%)	1.0	0.1	0.8	0.1	0.9	0.1
COD_t (g/L)	40.7	1.3	--	--	36.2	3.6

TS – Total solids
VS – Volatile solids
FS – Fixed solids

Table 3 – Organic loading rate (OLR) during each study phase. **(Back)**

Phase	Digester	SRT	Avg OLR*	*s.d.*
1	SSM	20	1.47	*0.13*
	SST	10	2.95	*0.26*
	Meso	10	1.49	*0.18*
	TPAD	20	2.46	*0.19*
2	SSM	15	2.03	*0.26*
	SST	20	1.52	*0.19*
	SST	5	6.08	*0.77*
	Meso	10	1.52	*0.14*
	TPAD	15	4.17	*0.49*
3	SSM	15	2.12	*0.18*
	SSM	25	1.28	*0.11*
	SST	7.5	4.25	*0.36*
	Meso	7.5	2.00	*0.12*
	TPAD	15	3.57	*0.25*

SRT - days
*** OLR (g VS/L*day)**
SSM – Single stage mesophilic
SST – Single stage thermophilic
Meso – 2nd stage mesophilic
TPAD – Temperature phased anaerobic digestion system

Table 4 – Average alkalinity and pH conditions. **(Back)**

Phase	Digester	Alkalinity*	*s.d.*	pH	*s.d.*
1	SSM20	4441	*446*	7.50	*0.21*
	SST10	4433	*525*	7.68	*0.24*
	TPAD10/10	4671	*789*	7.78	*0.19*
2	SSM15	5185	*230*	7.44	*0.05*
	SST20	5236	*143*	7.71	*0.10*
	SST5	4633	*477*	7.45	*0.28*
	TPAD5/10	5901	*367*	7.63	*0.09*
3	SSM15	--	--	7.45	*0.11*
	SSM25	--	--	7.38	*0.10*
	SST7.5	--	--	7.60	*0.12*
	TPAD7.5/7.5	--	--	7.70	*0.12*

*** mg/L as CaCO3.**
SSM – Single stage mesophilic
SST – Single stage thermophilic
TPAD – Temperature phased anaerobic digestion

Table 5– Free ammonia concentration in the single stage thermophilic and mesophilic digester at 20 day solids retention time. (Back)

	Temperature (K)	pKa	pH	Ammonium (mg/L as N)	Ammonia (mg/L as N)
SSM20	308	8.95	7.5	956	32
SST20	328	8.41	7.7	1392	230

SSM – Single stage mesophilic
SST – Single stage thermophilic

Table 6 – VFA concentration and distribution for each digester. (Back)

Phase	Digester	Avg. C2-C4 VFA (mg/L as acetic acid)	s.d.	Percent Distribution		
				C2	C3	C4
1	SSM20	532	181	60.9	21.1	18.0
	SST10	1463	460	30.0	63.2	6.8
	TPAD10/10	1031	293	36.8	53.9	9.3
2	SSM15	129	200	25.2	48.6	26.2
	TPAD5/10	603	300	84.7	9.9	5.4
	SST20	1364	597	44.2	48.3	7.5
	SST5	2367	831	20.6	70.4	9.0
3	SSM25	94	173	60.0	22.0	18.0
	SSM15	154	228	82.7	6.3	11.0
	TPAD7.5/7.5	192	180	76.5	13.8	9.7
	SST7.5	1067	754	32.0	60.4	7.6

VFA – Volatile fatty acid (acetic, propionic, butyric)
SSM – Single stage mesophilic
SST – Single stage thermophilic
TPAD – Temperature phased anaerobic digestion

Table 7 –Composition of biogas in each digester. **(Back)**

	Phase 1			Phase 2				Phase3			
%	**SSM20**	**SST10**	**Meso10**	**SSM15**	**SST20**	**SST5**	**Meso10**	**SSM25**	**SSM15**	**SST7.5**	**Meso7.5**
AVG CH_4	66	59	53	58	58	58	60	60	62	57	65
s.d.	10	4	9	7	4	3	--	5	4	5	2
AVG CO_2	31	40	31	33	36	34	23	33	37	38	25
s.d.	9	8	8	3	4	9	--	7	5	5	2

SSM – Single stage mesophilic
SST – Single stage thermophilic
Meso – 2nd stage mesophilic

Table 8 – Average NH_4-N concentration (mg/L) in the digesters. (Back)

Phase	Digester	n	Avg	*s.d.*
1	SSM20	12	956	*101*
	SST10	10	927	*236*
	TPAD10/10	11	1050	*246*
2	SSM15	11	1072	*72*
	SST5	11	1306	*92*
	SST20	11	1392	*150*
	TPAD5/10	11	1230	*147*
3	SSM25	14	1002	*78*
	SSM15	14	992	*78*
	TPAD7.5/7.5	15	1203	*76*
	SST7.5	13	1067	*60*

SSM – Single stage mesophilic
SST – Single stage thermophilic
TPAD – Temperature phased anaerobic digestion

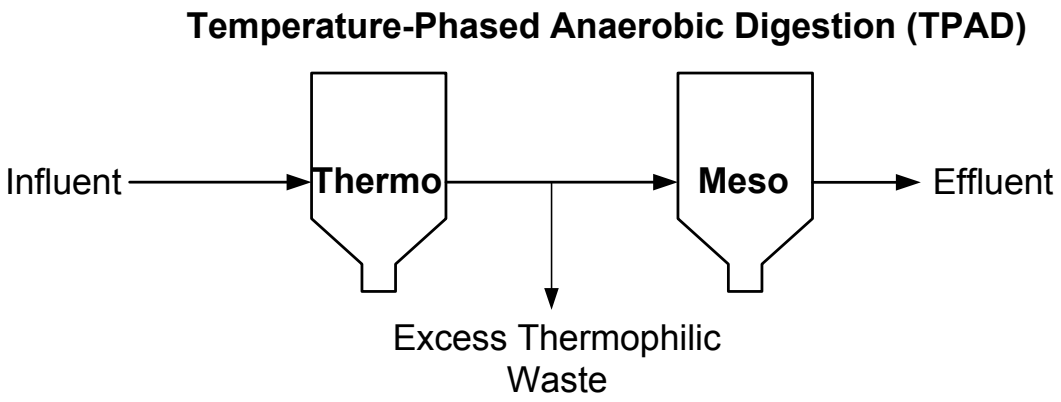

Figure 1 – General flow diagram for temperature-phased digestion systems in this study. **(Back)**

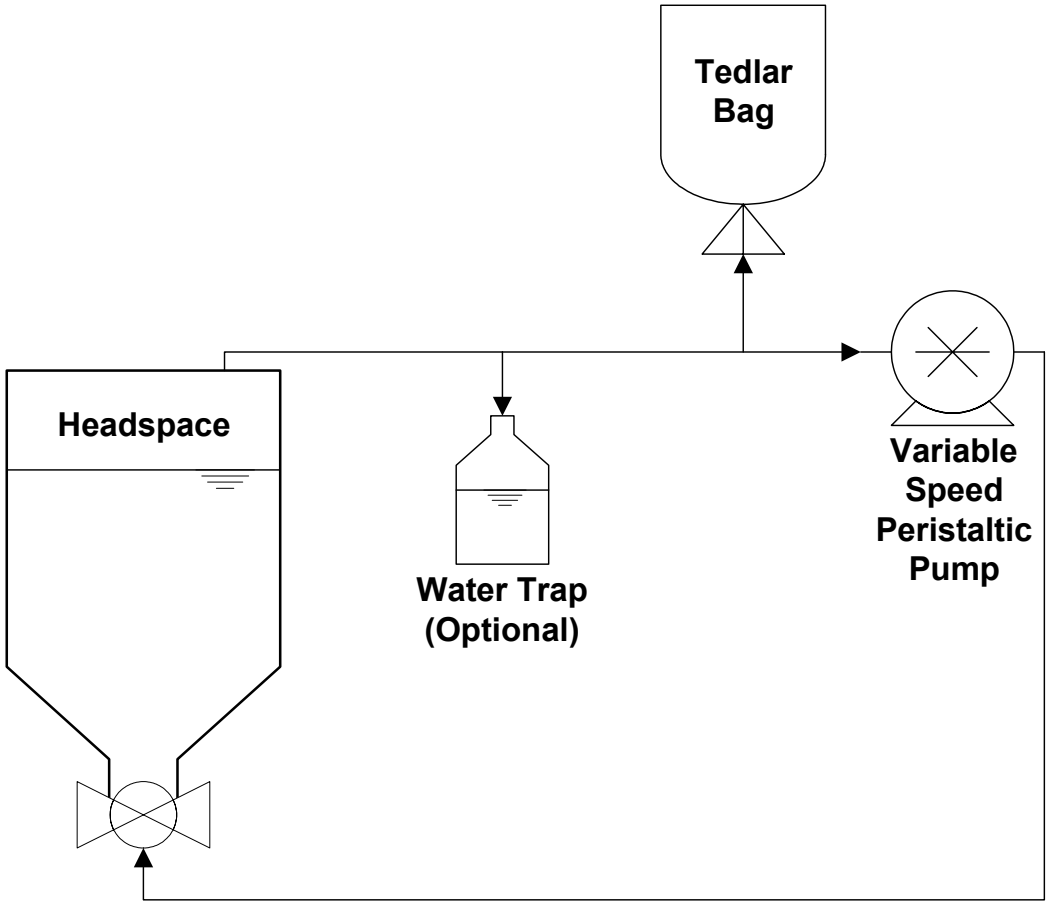

Figure 2 – Gas recirculation diagram for experimental setup. Water trap was utilized on the thermophilic reactor to prevent condensation from accumulating in the gas lines. **(Back)**

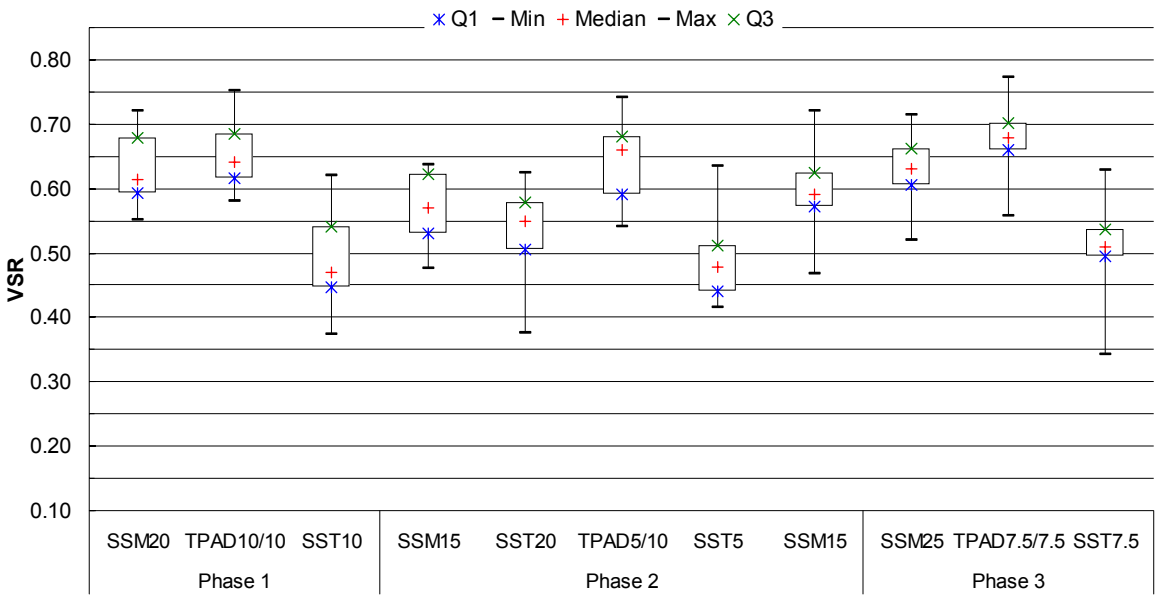

Figure 3 – Volatile solids reduction comparison between single stage mesophilic (SSM) and temperature phased anaerobic digestion (TPAD) systems during each test phase. **(Back)**

SSM – Single stage mesophilic
SST – Single stage thermophilic
TPAD – Temperature phased anaerobic digestion

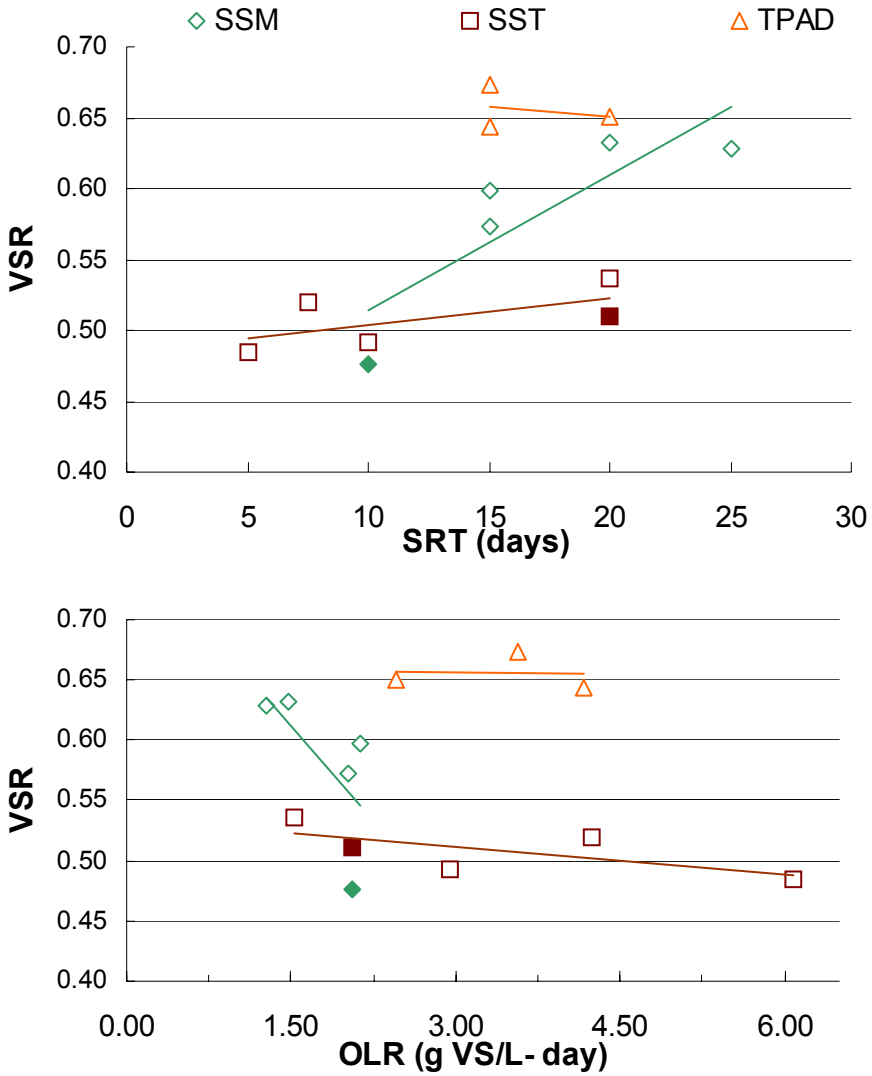

Figure 4 – Volatile solids reduction versus SRT and OLR for the digesters. Solid points represent data collected after the conclusion of this study but under similar conditions. **(Back)**

SSM – Single stage mesophilic
SST – Single stage thermophilic
TPAD – Temperature phased anaerobic digestion

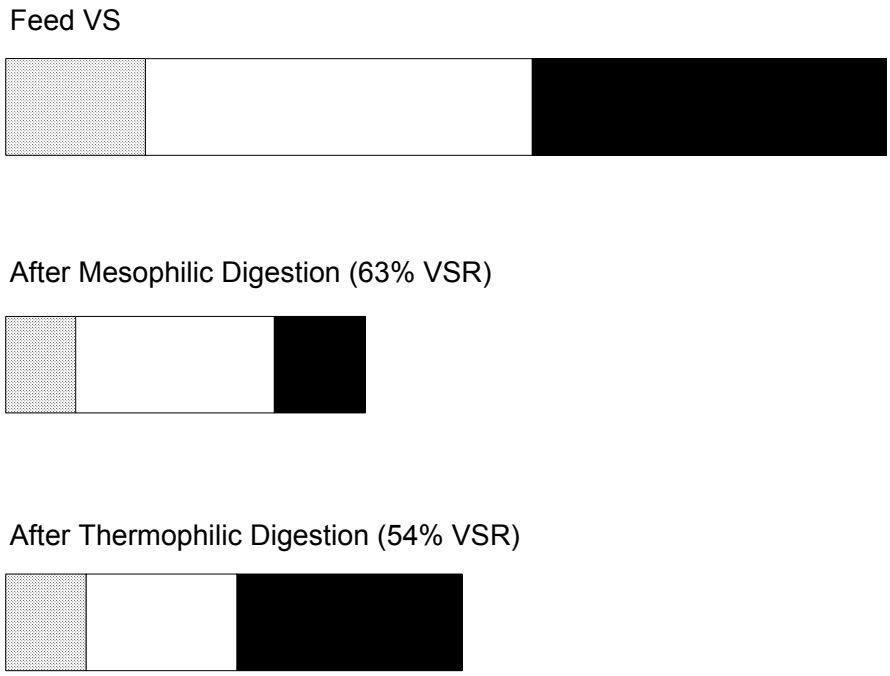

Figure 5 – Speculated differences if feed degradation by mesophilic and thermophilic biomass.
(Back)

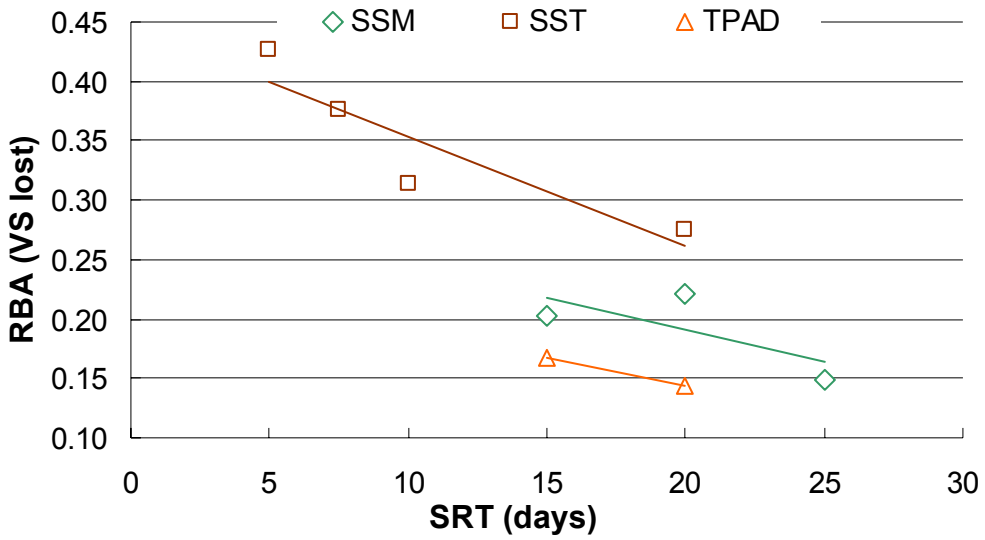

Figure 6– Residual biological activity test results. **(Back)**

SSM – Single stage mesophilic
SST – Single stage thermophilic
TPAD – Temperature phased anaerobic digestion

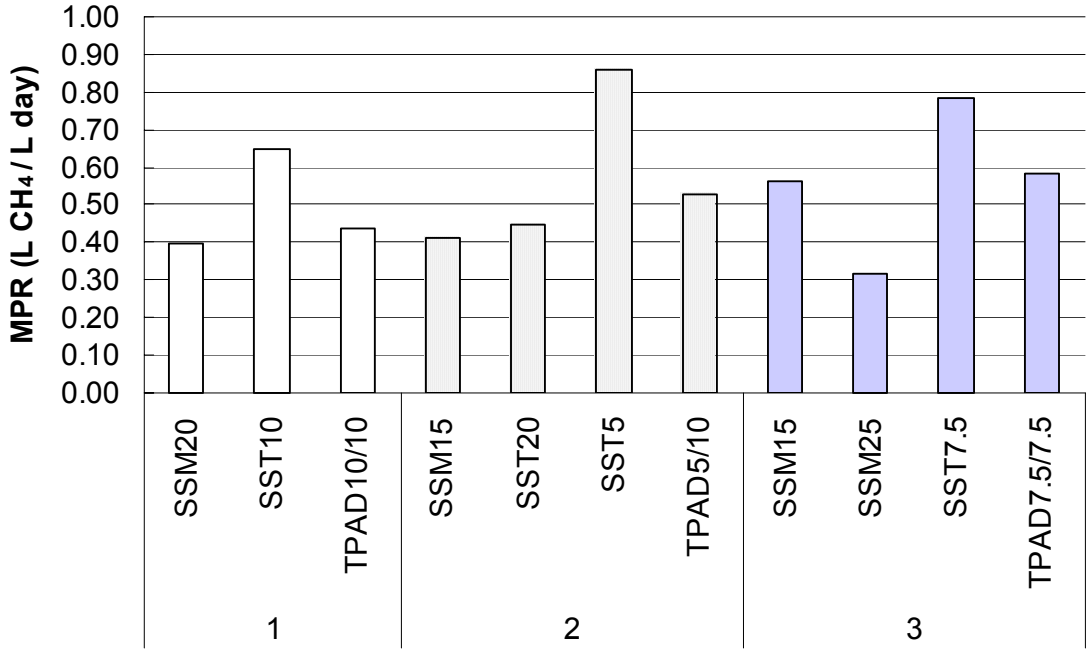

Figure 7 – Methane production rate (MPR) during each test phase. **(Back)**

SSM – Single stage mesophilic
SST – Single stage thermophilic
TPAD – Temperature phased anaerobic digestion

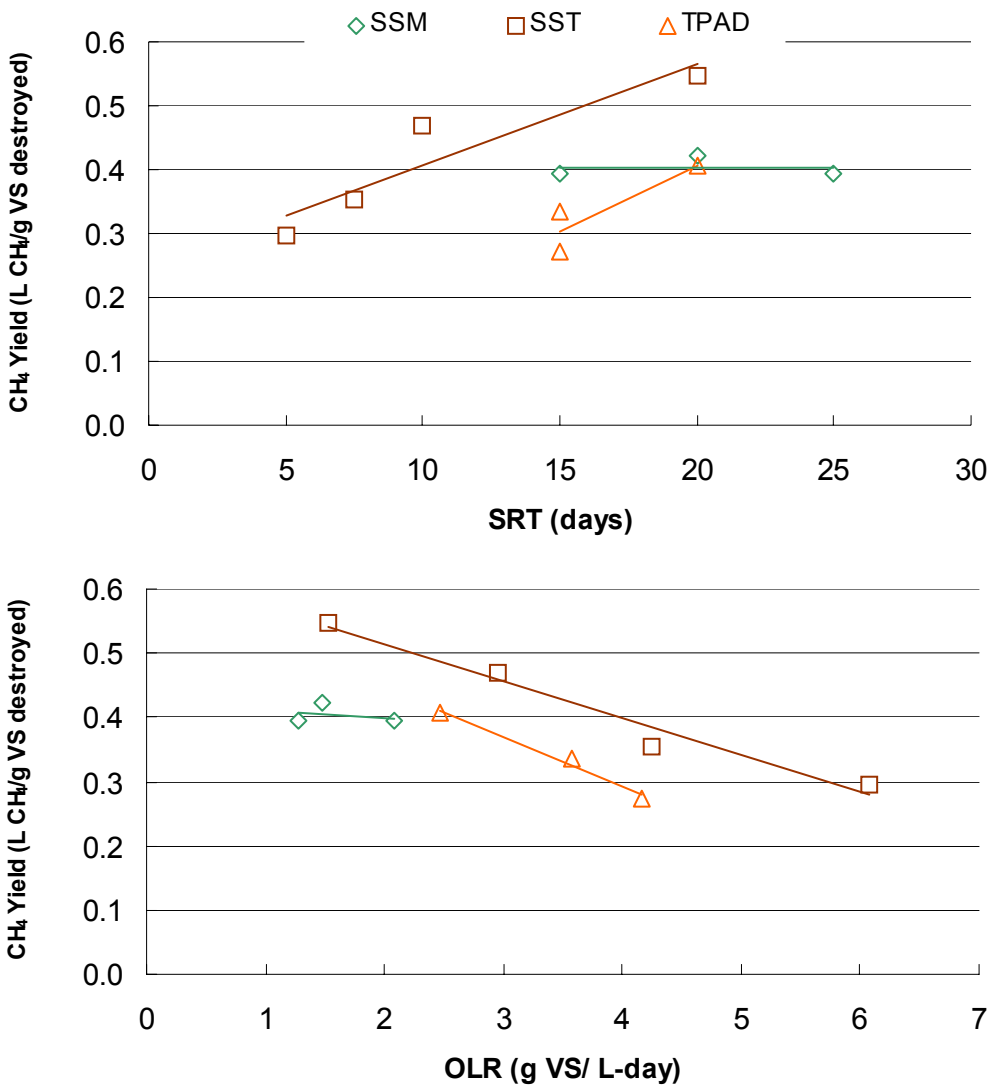

Figure 8 – Specific methane yield (at STP) for each digester system. **(Back)**

SSM – Single stage mesophilic
SST – Single stage thermophilic
TPAD – Temperature phased anaerobic digestion

Vita

David Inman was born on March 28, 1976, in Wichita Falls, TX. Graduating in 1994 from Tishomingo High School, Tishomingo, OK, he then attended the United States Naval Academy, Annapolis, MD, from 1994 to 1996. He graduated from Salisbury University, Salisbury, MD, with a B.S. in Environmental Health Science in December 1998.

His professional experience includes working for Perdue Farms Incorporated, a Mid-Atlantic agribusiness, as an Environmental Manager from 1999 to 2002. Job duties in this position included monitoring permit compliance at several of the company's processing and support facilities. The experience with wastewater treatment and biological nutrient removal at Perdue Farms led him to begin pursuing an Environmental Engineering degree at Virginia Tech in August 2002. Currently, he is employed as a Project Engineer at Anderson and Associates, Inc., Blacksburg, VA.

He and his wife, Sara, reside in Blacksburg where in his spare time he enjoys woodworking, spending time outdoors, and reading.