Sludge Stabilization Sustainability of Aerobic Digestion Processes

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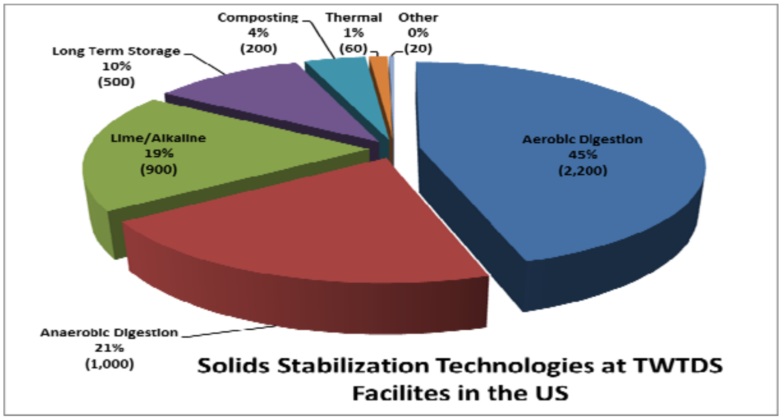
ABSTRACT

Treating wastewater is very important to protect the quality of human life and preserve water resources. Justifiably a lot of time, consideration, money, and resources are dedicated to designing a wastewater treatment. One of the main objectives of a wastewater treatment plant is liquid and solids separation. Much emphasis is placed on providing an optimal liquid treatment process at a wastewater treatment facility because after all wastewater is mostly comprised of water. Although the solids is a relatively small portion of wastewater the processing, treatment, and disposal of solids generated from a wastewater treatment plant accounts for a substantial percentage of total wastewater treatment plant expenditures. According to the Global Atlas of Wastewater Sludge and Biosolids Management the estimated percentage of total wastewater costs required for wastewater sludge management in the United States was 57% and in developed countries such as Canada, China, Japan, and Austria was 44%, 40%, 37%, and 45% respectively (United Nations Human Settlements Programme, 2008). These costs will only continue to rise because the amount of sludge produced at wastewater treatment plants is continually increasing. The USEPA estimated the sewage sludge production in 1998 from publicly owned treated works (POTW) facilities in the United States was 6.9 million dry tons (US EPA, 1999) and was estimated at 8 million dry tons in 2005 (US EPA, 2006). High expenditures associated with solids management at a wastewater treatment facility can also be a direct result of a lack of emphasis to provide the most efficient and effective solids handling process. The solids handling process is typically the first thing that is considered for cost reductions or eliminated altogether whenever a bid for constructing a new facility or major upgrade to a wastewater treatment plant goes over the anticipated budget.

Commonly utilized processes used to stabilize solids generated from wastewater treatment plants include anaerobic digestion, aerobic digestion, lime/alkaline stabilization, composting, long term storage in lagoons or reed beds, thermal processes, and incineration. Due to many large communities that exist in California anaerobic digestion processes are the most commonly operated solids stabilization process utilized at wastewater treatment plants because they are ideal to treat facilities with larger flow rates (more than 5 million gallons per day). In fact 82% of treatment works treating domestic sewage (TWTDS) facilities in California utilize anaerobic digestion stabilization processes (Northeast Biosolids and Residuals Association, 2007). However, in 2005 there were approximately 4,880 TWTDS facilities in the United States and of those facilities 2,200 are using aerobic digestion processes (United Nations Human Settlements Programme, 2008). Per Figure 1 below this means 45% which is a high majority of TWTDS facilities in the United States operate aerobic digestion systems to stabilize solids and is the most commonly used solids stabilization technique to treat domestic sewage solids in the United States. Due to this fact it is worthy of investigating and providing information on what can make this process sustainable.

Figure 1: Solids Stabilization Technologies at TWTDS Facilities in the United States (Global Atlas of Wastewater Sludge and Biosolids Management, 2008)



INTRODUCTION AND LITERATURE REVIEW

Many engineers that design wastewater treatment facilities that are considering an aerobic digestion stabilization systems believe that it is as simple as aerating a tank. To have a sustainably efficient aerobic digestion system it is not that easy. Everybody is certainly entitled to their own opinions and beliefs but one might ask a very important and logical question. Will designing the aerobic digestion process as an aeration tank provide the best optimization and sustainability? While it is best to always keep things simple there is a lot more to an aerobic digestion system then this rationale. With this kind of approach it is not a surprise that solids management expenditures are so high and can be minimized with the correct design as well as optimized operations. While in general aerobic digestion is a relatively simple process there are many design and operational parameters such as temperature control, oxygen transfer and mixing, nitrification and denitrification, solids retention time, pH control, sludge loading characteristics, and tank configuration that must be considered in order to achieve a sustainable process.

Although aerobic digestion is the most commonly utilized solids stabilization process at TWTDS in the US more research and studies have been dedicated to anaerobic digestion processes. The reasons for this are that although there is half the amount of anaerobic digestion systems at TWTDS compared to aerobic digestion processes it is reasonable to assume anaerobic digestion systems treat a majority of the flow since most aerobic digestion systems are utilized at facilities less than 5 MGD. In addition, anaerobic digestion processes are much more complex than aerobic digestion systems due to the process sophistication of converting biogas into electricity which may be a reason why it has been studied in more depth.

A thorough search of technical documents on Google Scholar revealed there not as many studies conducted on aerobic digestion processes compared to anaerobic digestion processes, however it is still a pretty highly studied process. Common studies for aerobic digestion include: aerobic digestion under thermophilic conditions, temperature effects on aerobic digestion, sludge digestion using aerobic and anoxic cycles, and nitrogen removal in aerobic digestion processes.

This study will focus on aerobic digestion under mesophilic conditions so the abundance of studies done on aerobic digestion under thermophilic conditions will not be very useful. Many of the studies that have been conducted seem to focus in a very specialized area.

More than 50 technical documents such as journal papers, books, and manuals were reviewed for this study. While some of the documents describe one or two optimization techniques and some design considerations of aerobic digestion processes an overwhelming majority of the documents do not go into detail regarding all of the aerobic digestion optimization techniques nor provide data from operating facilities. Wastewater Engineering Treatment, Disposal, and Reuse, Third Edition by Metcalf and Eddy is a common utilized reference for the design of wastewater treatment plants and has provided some simplified aerobic digestion process design guidelines such as tank sizing which is based on 10-20 days SRT, air requirements based on mixing requirements between 20 scfm to 40 scfm per 1,000 cubic feet, and provide typical volatile solids loading rates (Metcalf and Eddy, 1991). While these guidelines provide a very simplistic approach they do not go into the detail required to fully optimize an aerobic digestion process and do not believe it is the intention to collect and examine data from operating aerobic digestion facilities.

Some have performed optimization studies of aerobic digestion processes, however there have been few studies done with supporting process and economic data. The Operation of Municipal Wastewater Treatment Plants, Manual of Practice No. 11, Volume III Solids Processes, Sixth Edition by the Water Environment Federation (WEF) provides very useful information on studies conducted on aerobic digestion optimization techniques. Per this manual, in 1997, Dr. Glenn Daigger outlined aerobic digester optimization techniques as well as the advantages and disadvantages to them. Also noted in this manual, Enviroquip a company with more than forty years of experience with aerobic digestion processes studied optimization techniques of aerobic digestion processes implemented at several different facilities that utilize thickening and temperature control and determined using these techniques require much shorter solids retention time (SRT) to meet the minimum 38% volatile solids destruction requirement for Class B Biosolids stabilization and at temperatures lower than 10^{o} C volatile solids destruction can be as low as 16%. Also observed from the aerobic digestion facilities in the Enviroquip study was low dissolved oxygen (DO) conditions did not affect volatile solids performance while high DO conditions caused low pH (Water Environment Federation, 2007).

Although the aerobic digestion process research highlighted in the WEF Manual of Practice No. 11 and the others associated with aerobic digestion process optimization show very detailed and useful process data such as volatile solids reduction, DO, temperature, and pH, there is a lack of data showing the effectiveness of the implementation of the optimization techniques because there are lack of comparisons to the existing systems of the plants to show how much improvement the enhancement techniques have. Also there has been little mention about the economic impacts that support the implementation of aerobic digestion process optimization and what the economic consequences were from the previous process operation. Furthermore, there are few examples that show the process enhancement techniques improve other wastewater treatment processes such as dewatering or the biological liquid treatment process. Wastewater treatment processes must show outstanding process performance as well as provide substantial economic benefits for a long duration in order to be considered sustainable. The main purpose of this research is to identify optimization techniques that make an aerobic digestion system a sustainable solids stabilization process, analyze process data that supports the implementation of process optimization, evaluate economic data as a result of utilizing process optimization to determine not only the effectiveness but also the economic benefits and repercussions, and examine the importance aeration and mixing plays in aerobic digestion process performance and sludge stabilization sustainability.

In addition, operating data, operational expenditures, cost analysis, feasibility reports from numerous aerobic digestion facilities was provided from various engineers and wastewater treatment plant operators. Relevant data provided from operating aerobic digestion systems included volatile solids reduction performance, temperature, pH, solids concentrations of sludge, and nitrogen and phosphorus concentrations in supernatant. Operating expenditure information that was provided included energy, disposal, operation and maintenance, and chemical costs. Cost analysis and feasibility reports provided information such as capital and operating costs estimates of various solids handling systems considered as well as data on existing systems.

METHODOLOGY

In order to research the sludge stabilization sustainability of aerobic digestion processes one must know what is it, how it works, what are the advantages and disadvantages, and what are the primary objectives?

Aerobic digestion is a solids stabilization process that provides a limited supply of oxygen to microorganisms in order to facilitate oxidation of organic matter and convert it into carbon dioxide and water. The microorganisms utilized in aerobic digestion processes are mesophilic facultative bacteria which mean they thrive in temperatures between 20 ^{o}C and 37 ^{o}C and live under aerobic (presence of oxygen), anoxic (no oxygen but presence of nitrates), and anaerobic (no presence of oxygen or nitrates) conditions. Often many confuse an aerobic digestion process with an activated sludge process. Although similar to an activated sludge liquid treatment process which promotes growth of microorganisms and are operated under high dissolved oxygen (DO) conditions typically at 2 mg/L or more, an aerobic digestion process is a decay process operated under low DO conditions. Aerobic digestion systems are operated at a DO ranging typically between 0.5 mg/L to 1.0 mg/L in order to promote competition of microorganisms for a limited oxygen supply. In fact it was studied by Ju that DO conditions under 0.3 mg/L in aerobic digestion systems do not adversely impact volatile solids reduction or pathogen removal performance and that high DO causes low pH which can be detrimental since mesophilic bacteria are sensitive to pH conditions (Enviroquip, 1999). The microorganisms that are out competed for oxygen must consume a portion of their cellular protoplasm in order to obtain energy for cell maintenance. However, only about 75% to 80% of the cell tissue can be oxidized while the remaining 20% to 25% is composed of inert and organic compounds that are not biodegradable (Metcalf and Eddy, 1991). This process is known as endogenous respiration and is how biomass or volatile solids destruction is achieved.

An aerobic digestion system typically consists of two or more aerated tanks used to process and store waste activated sludge (WAS) generated from the liquid treatment process and/or primary sludge (PS) from primary sedimentation tanks. The WAS and PS in an aerobic digestion system can be processed separately or can be combined into one product. Air is introduced to the tank(s) from an aeration system typically coarse or fine bubble diffuser equipment with the air being supplied by a positive displacement or centrifugal blower.

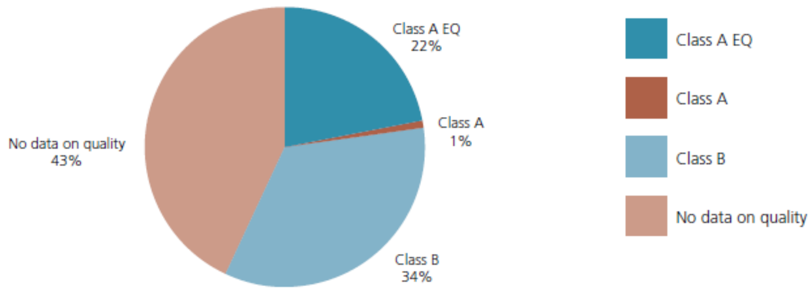
The main objectives of aerobic digestion processes are to produce biosolids that are stable and amenable to various beneficial uses such as land application, reduce pathogens (disease causing organisms), and control odors. Approximately 55% of biosolids produced in the United States were for applied for beneficial use such as land restoration, agronomic, and silvicultural purposes while the remaining 45% were disposed of at municipal solid waste landfills or incineration facilities (United Nations Human Settlements Programme, 2008). Prior to 1993 there were no performance requirements or standards for the application of sewage sludge and aerobic digestion systems were designed based on 10-20 days solids retention time (SRT) and a mixing air requirement of 30 standard cubic feet per minute (scfm) per 1,000 cubic feet of aerobic digester volume. In 1993 due to issues with vectors and pathogens associated with the land application of sewage sludge the United States Environmental Protection Agency (EPA) adopted Title 40 – Protection of the Environment Code of Federal Regulations (CFR) Part 503 "Standards for the Use or Disposal of Sewage Sludge" classifies two typical levels of solids stabilization in order to land apply sewage sludge and they are Class A and Class B. Class A sludge is stabilized to essentially eliminate pathogens while Class B sludge is stabilized where pathogens are significantly reduced but still present in large numbers. Class A sludge can be used without restriction to be applied to home gardens, lawns, and can be sold or given away in bags or containers. Class B sludge is can be used for application to agricultural or nonagricultural land (US EPA, 1993).

To meet Class A stabilization the following criteria must be met: a fecal coliform density less than 1,000 most probable number (MPN) per gram of total dry solids or salmonella density less than 3 MPN per 4 grams of total dry solids (US EPA, 1993).

In order to meet Class B stabilization two criteria must be met per the EPA Title 40 – CFR Part 503 Regulations. The first criteria that must be met is Pathogen Reduction and this can be met by complying with one of these two requirements: 1) Pathogens in the sewage sludge containing less than 2,000,000 CFU per gram of total dry solids and 2) Meeting a time temperature requirement of 20^{o} C at 40 days SRT or 15^{o}C at 60 days SRT. The second criteria is the Vector Attraction and can be met by meeting one of these two requirements: 1) Volatile solids reduction of 38% or more or 2) Standard Oxygen Uptake Rate (SOUR) of 1.5 milligrams oxygen per hour per gram of dry solid (mg O_2/g VSS/hr) or less (US EPA, 1993). For example if a sludge sample has a SOUR of 1.49 mg O_2/g VSS/hr and pathogens of 1,999,999 CFU per gram of total dry solids then it is in compliance with Class B stabilization requirements.

In 2004 approximately 7,180,000 dry tons of solids were produced in the US, and from this total 23% was treated to Class A standards, 34% to Class B standards, and the remaining 43% the United Nations Human Settlements Programme did not obtain data because wastewater solids taken to a landfill are generally not subjected to stabilization testing or reporting requirements (United Nations Human Settlements Programme, 2008). Figure 2 below outlines biosolids treatment levels in the United States in 2004.

Figure 2: Biosolids Treatment Levels, 2004 U.S. Totals (Global Atlas of Wastewater Sludge and Biosolids Management, 2008)



The performance of an aerobic digestion system is typically based on volatile solids destruction which is an indicator of sludge stabilization. However, volatile solids reduction may not be the best indicator of sludge stabilization or aerobic digestion performance. For instance, if one system achieves 50% volatile solids reduction and another system achieves 30% volatile solids reduction, does it mean that the system with 50% volatiles solids reduction is a better performing system and has a more stabilized product than one achieving only 30%? Not necessarily. As noted above SOUR can also be used to meet the Vector Attraction Requirement of the EPA Title 40 – CFR Part 503 Regulations. The SOUR is a good indicator of how much biodegradable organics are in the sludge hence indicating how stabilized sludge is. The SOUR is the amount of oxygen used by microorganisms to burn volatile solids. A low SOUR means that there is not a lot of VS to burn in the solids. It is recommended to use the SOUR requirement for systems where the feed sludge being processed has low VS content. Utilizing the Van Kleeck Equation (Equation 1 below) to determine volatile solids reduction, sludge with 85% VS processed to 75% VS content results in a volatile solids reduction of 47%. Compared to sludge with 70% VS content that is processed to 60% VS results in a volatile solids reduction of 35.7%. As demonstrated reducing the volatile fraction of the solids 10% in both cases results in different volatile solids reduction. Going from 85% VS to 75% VS results in more volatile solids reduction than reducing from 70% to 60% which does not meet the Vector Attraction criteria for volatile solids reduction standards of the EPA Title 40 – CFR Part 503 Regulations. However sludge that is reduced to 60% has 50% less volatile solids content than sludge reduced down to 75%. This confirms that if sludge has higher volatile fraction it is much easier to achieve volatile solids reduction because of the presence of more readily biodegradable organics then one with lower volatile content. It is the same concept that it would be easier for a 400 pound obese person to lose weight then a skinny 150 pound person. To conclude the SOUR is a better indicator of sludge stabilization then volatile solids reduction for a solids handling system including aerobic digestion. The SOUR is becoming a more common testing procedure for most operators instead of using the traditional volatile solids reduction (Water Environment Federation, 2007).

Equation 1: Van Kleeck Equation for Determining Volatile Solids Reduction

$$Volatile\ Solids\ \mathrm{Re}duction\,(\%) = \left(\frac{VS_{IN} - VS_{OUT}}{VS_{IN} - (VS_{IN}\,x\,VS_{OUT})}\right) x100\%$$

The advantages of aerobic digestion processes include low capital cost, low nitrogen and phosphorus in supernatant compared to anaerobic digestion processes, simple and robust operation, and ideal for treatment to Class B land application requirements. The main disadvantages to this process is it has high energy costs associated with blowers used to provide air to the system, difficult to achieve Class A treatment since aerobic digestion requires a substantial quantity of microorganisms to stabilize the sludge, it is primarily used at facilities less than 5 million gallons per day (MGD), and reduced efficiency during cold weather operations due to microbial activity being severely hindered. Aerobically digested sludge also has poor dewatering characteristics compared to anaerobically digested sludge since it contains less readily biodegradable organics. The typical dewatered cake solids for aerobic digested PS plus WAS is typically between 16% and 25% with a centrifuge and 12% and 20% with a belt filter press. Compared to dewatered anaerobically digested PS plus WAS is between 22% to 32% with a centrifuge and 18% to 44% with a belt filter press (US EPA, 2000).

Aerobic Digester Chemistry

Since an aerobic digestion process utilizes microorganisms to degrade organics it is important to understand chemistry and certain biological processes such as nitrification and denitrification. An aerobic digestion system is based on first order kinetic reactions and has the following three processes: 1) biomass destruction, 2) nitrification, and 3) denitrification.

In the biomass destruction process the microorganisms use oxygen to produce the following byproducts: carbon dioxide, water, and ammonium bicarbonate, a form of alkalinity. If additional oxygen is provided beyond what is required for biomass destruction the nitrification process will occur. In the nitrification process ammonium is converted into nitrate while two moles of acidity (H^+) are produced and a loss of two moles of alkalinity. If oxygen continues to be provided after the nitrification process has occurred, acid production will continue resulting in lower pH and destroy alkalinity to neutralize the acid. This circumstance can kill the biomass since microorganisms are very sensitive to low pH conditions. In order to prevent excessive acid accumulation the denitrification process must occur. Denitrification is the biological reduction of nitrate (NO_3) into nitrogen gas by facultative heterotrophic microorganisms. There are three items required to achieve denitrification: 1) heterotrophic bacteria, 2) nitrate which is used as an energy source by the microorganisms to metabolize and oxidize organic matter and, 3) organic matter which serves as a food source for the heterotrophic bacteria to survive. Carbon requirements are a very important aspect of the denitrification process. As a rule of thumb a 6:1 carbon to nitrogen ratio is required to achieve complete nitrogen removal. Denitrification in an aerobic digestion process can be achieved by cycling the air off resulting in the absence of oxygen thus oxidizing the biomass with nitrates as an electron acceptor. When denitrification is accomplished in an aerobic digestion process nitrate is converted into nitrogen gas and in a complete nitrification – denitrification process carbon dioxide, alkalinity, and water are produced. Table 1 below shows stoichiometric equations associated with the steps in an aerobic digestion process.

Table 1: Aerobic Digestion Chemistry Equations (Operation of Municipal Wastewater Treatment Plants, Manual of Practice No. 11, Volume III Solids Processes, Sixth Edition)

Process	Equation
Biomass Destruction in Aerobic Digestion	$C_5H_7NO_2 + 5O_2 = 4CO_2 + H_2O + NH_4HCO_3$
Nitrification	$NH_4 + 2O_2 = H_2O + 2H^+ + NO_3$
Biomass Destruction with Nitrification	$C_5H_7NO_2 + 7O_2 = 5CO_2 + 3H_2O + H^+ + NO_3$
Denitrification	$C_5H_7NO_2 + 4NO_3 + H_2O = + NH_{4\,+}\ 5HCO_3 + 2N_2$
Complete Nitrification-Denitrification	$C_5H_7NO_2 + 5.75O_2 = 5CO_2 + 3.5H_2O + 0.5N_2$

There are five key optimization techniques that provide sludge stabilization sustainability of an aerobic digestion process which will be examined in this study. The five optimization techniques are as follows: 1) Tank Configuration, 2) Thickening, 3) Aerobic and Anoxic Control, 4) Temperature Control, and 5) Operational Flexibility (Water Environment Federation, 2007)

In addition to the optimization techniques, in order for an aerobic digestion process to provide sustainable sludge stabilization, it must have an adequate aeration and mixing system. Since an aerobic digestion system relies on microorganisms to break down organic matter, the way oxygen is supplied to them is extremely important.

DISCUSSION AND RESULTS

Tank Configuration

Aerobic digesters are considered continuous stirred tank reactors (CFSTR) therefore tank configurations are very critical to the performance of these systems. The tanks can be configured in series, parallel, or multiple trains of tanks operating in series or parallel. Equation 2 describes first order reaction mass balance of a single CFSTR reactor while equation 3 is for CFSTR operating in series.

Equation 2: First Order Reaction Mass Balance Equation of a Single CFSTR

$$\frac{C_{OUT}}{C_{IN}} = \frac{1}{1 + k(V/Q)} = \frac{1}{1 + k\tau}$$

Equation 3: First Order Reaction Mass Balance Equation of CFSTRs in Series

$$\frac{C_{OUT}}{C_{IN}} = \left(\frac{1}{1 + k(V/Q)}\right)^n$$

Where:

- C_{OUT} = Effluent Concentration
- C_{IN} = Influent Concentration
- k = First order reaction rate (time^{-1})

- V = Total Volume
- Q = Flow Rate
- n = Number of Reactors

For example let's compare the effluent total solids concentration of the following four aerobic digestion systems that will each process 100,000 gallons per day of sludge with an influent total solids concentration of 30,000 mg/L and first order reaction rate of 0.1/day: 1) A single tank 2,000,000 gallon system, 2) Two tanks each 1,000,000 gallons operating in parallel, 3) Two tanks each 1,000,000 gallons operating in series, and 4) A total three tanks of equal size with a total volume of 2,000,000 gallons where two tanks are in parallel and the third in series. Utilizing Equation 1 and Equation 2 above will determine the effluent TS removal results of each system. Figure 3 shows the configuration of each of the four systems while Table 2 shows the effluent total solids concentration results of the four cases.

Figure 3: Tank Configurations of Four Aerobic Digestion Systems

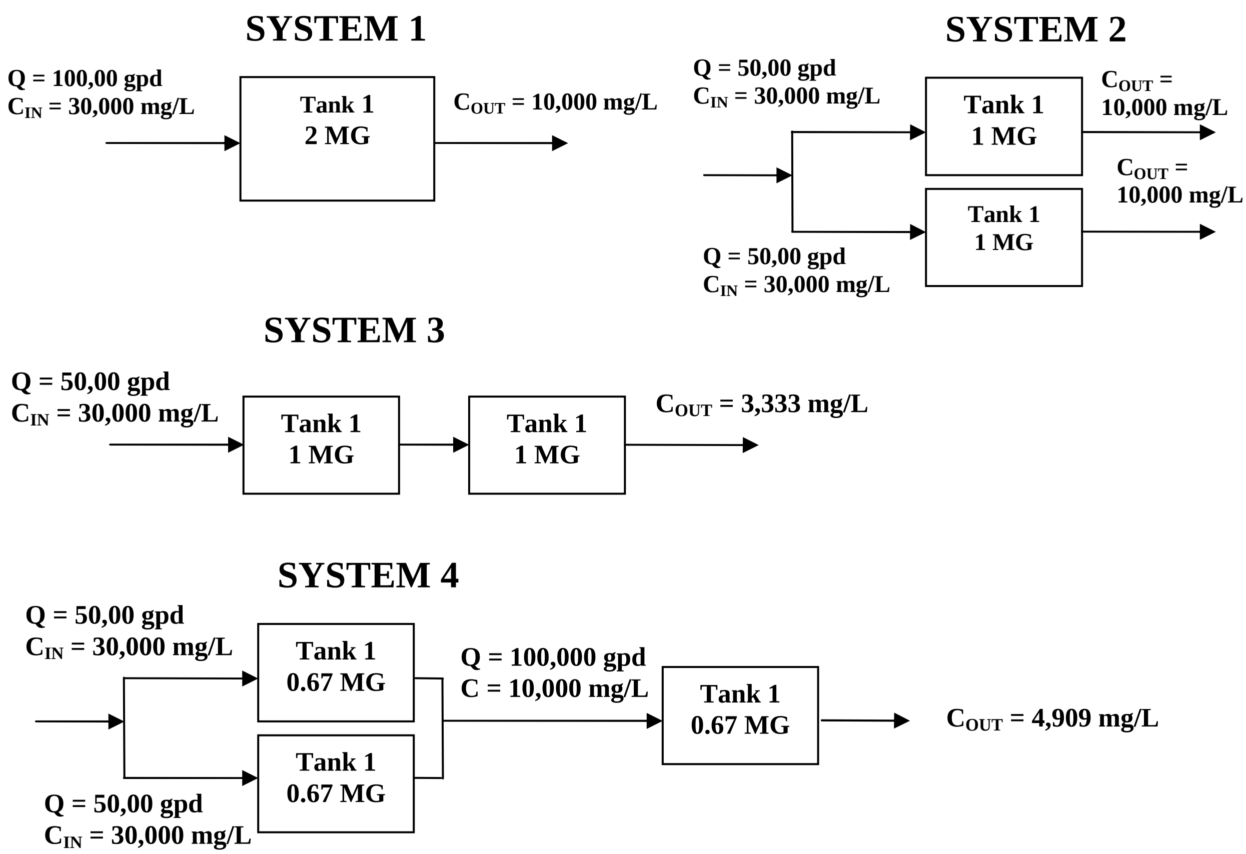


Table 2: Total Solids Removal of Various CFSTR System Configurations

	System 1	System 2	System 3	System 4
Effluent TS (mg/L)	10,000	10,000	3,333	4,909
Removal Efficiency (%)	67%	67%	89%	84%

Different reactor configurations even with the same total volume, first order reaction rate, flow rate, and influent TS concentration offered different effluent TS results. In conclusion removal efficiencies can depend on how reactors are configured. Based on the results of Table 2 above system 3 which two tanks operate in series has the best TS removal and efficiency of all systems while operating one tank and two tanks in parallel offered the lowest TS removal. Based on these findings a series operation of multiple tanks and combining the tanks in parallel or series offer the most efficient and effective aerobic digestion systems, while a single tank and parallel tank configurations offer the least efficient systems.

As discovered above a series operation of an aerobic digestion system offers the most effective removal efficiencies. Due to increased efficiency of a series operation per EPA Title 40 – CFR Part 503 Regulations a 30% time temperature reduction to meet the Pathogen Reduction requirement may be taken for this operation (US EPA, 1993). To clarify the time temperature requirement of 40 days SRT at 20^{o} C or 60 days SRT at 15^{o}C becomes the new standard of 28 days SRT at 20^{o} C or 42 days SRT at 15^{o}C if a system is operated in series. Using a series tank configuration allows aerobic digestion tanks to have reduced volumes and air requirements while maintaining efficiency.

Importance of Thickening to an Aerobic Digestion System

There are generally four ways sludge is thickened in aerobic digestion systems. Decanting where aeration is turned which allows solids to settle while the clear water above the settled sludge or supernatant is removed. Decanting is probably the most common thickening method due to its simplicity and very low capital costs. Aerobic digestion systems that utilize decanting for thickening are known as conventional aerobic digestion systems. While conventional aerobic digestion systems are widely operated it has some disadvantages such as unreliable and poor thickening performance compared to other thickening alternatives. For a conventional aerobic digestion system thickening performance relies solely on the settling characteristics of the sludge and for those systems processing only secondary WAS can even more impactful. The typical dry sludge solids concentration of WAS is typically 0.8% with primary settling can be thickened to typically 1.3% (Metcalf and Eddy, 1991). Poor thickening results in an aerobic digestion system with reduced SRT, reduced volatile solids reduction, increases in energy and disposal costs, and larger tank volumes to achieve adequate stabilization. Another disadvantage to a conventional aerobic digestion system is since thickening by decanting requires no aeration it can provide the opportunity for polyphosphate accumulating organisms (PAO) microorganisms to release P in the supernatant if anaerobic conditions are created from a long period with no aeration. The supernatant can also contain high total suspended solids content due to poor settling.

Sludge can also be thickened prior to being processed in aerobic digestion tanks utilizing a gravity thickener similar to a secondary clarifier. The advantages of this thickening technique is it is a conventional technology wastewater operators are familiar with and offers better thickening performance than decanting generally ranging between 2%-3% solids. Although gravity thickening offers a little better thickening performance than a conventional aerobic digestion process it has essentially the same disadvantages as a conventional aerobic digestion process.

Another pre-thickening technique that is used is a mechanical thickener such as a rotary drum thickener (RDT) or gravity belt thickener (GBT). A RDT consists of a sludge conditioning polymer feed system and rotating cylindrical screens. Polymer is mixed with a thin sludge such as WAS in a mixing drum. After the sludge is conditioned in the drum it is passed to the rotating screen which separates the flocculated solids from water. Thickened sludge rolls out of the end of the drums, while separated water decants through the screens (Metcalf and Eddy, 1991). A GBT consists of a polymer conditioning system and a gravity belt that moves over a series of rollers driven by a variable speed drive. The sludge is conditioned with polymer and fed into a box at one end. The box is used to distribute sludge evenly across the width of the moving belt as the water drains through and the sludge is carried toward the discharge end of the thickener. The sludge is lined by a series of plow blades placed along the travel of the belt which allows the water to be released from the sludge to pass through the belt. After the sludge is removed, the belt travels through a wash cycle (Metcalf and Eddy 1991). Mechanical thickeners offer excellent thickening performance and can thicken solids ranging between 4% and 8% and have lower energy usage. Mechanical thickeners are another conventional technology many wastewater operators are familiar with and are widely accepted. The disadvantages to mechanical thickening are high capital costs associated with the use of polymers and the construction of a building to protect them from outdoor elements. Attention required for mechanical equipment such as startup, cleanup, and shutdown time increases operating costs. There are also concerns with reduced oxygen transfer and mixing efficiency associated with aerating polymer thickened solids which are very viscous. Figure 4 below shows both a GBT and Figure 5 shows an RDT.

Figure 4: Gravity Belt Thickener

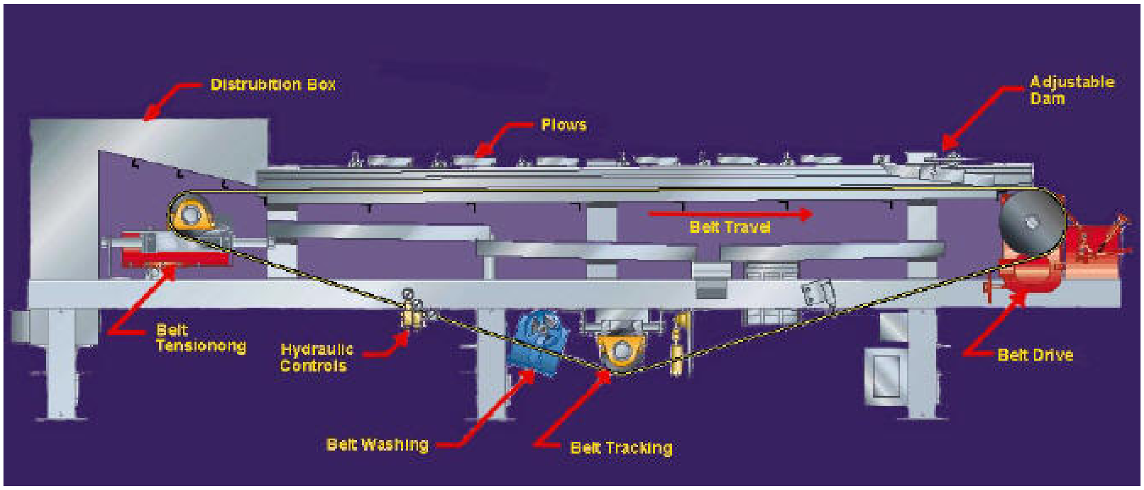
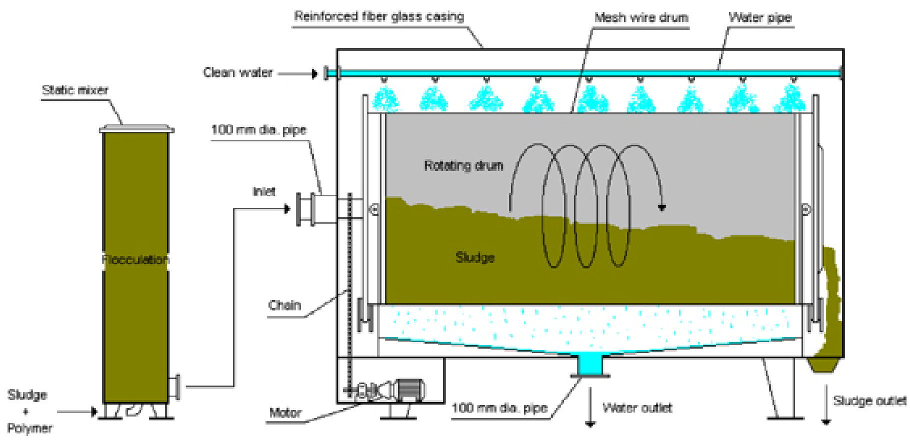


Figure 5: Rotary Drum Thickener



The last thickening technique in this discussion is thickening with a submerged flat plate membrane unit. Since this is a unique and different thickening technology much of the discussion for this research will be on this technology. Membranes are commonly known to be utilized in liquid treatment processes known as Membrane Bioreactor (MBR). However, they can also be integrated with a controlled aerobic digestion system. In a MBR process sludge is typically thickened to 1% solids but in an aerobic digestion process WAS is thickened up to 4% solids concentration. The first membrane thickening installation in the world was at the Miazaki WWTP in Miyazaki, Japan while the first installation in the United States was at Dundee WWTP in Dundee, Michigan commissioned in 2005 (Bailey and Steinberg, 2005). Figure 6 below shows a membrane thickening apparatus.

Figure 6: Submerged Flat Plate Membrane Thickening Unit

Wastewater is physically filtered out a submerged membrane unit (SMU) and is called permeate. This is accomplished because a coarse bubble diffuser located at the bottom of the unit creates a vacuum pressure gradient allowing for the wastewater to be filtered out of the sludge. The solids are left in the thickening tank while permeate is pumped via a progressive cavity or centrifugal pump to the head works of the plant or to disinfection. The diffuser also scours the membrane plates. This is very important because filtration performance relies heavily on biofilm management. Biofilm shown in Figure 7 are the microorganisms that accumulate on the membrane plate as permeate is filtered out of the sludge. The diffuser provides the scouring air to keep the biofilm at the appropriate thickness to prevent biological fouling. The biofilm acts as a secondary filter which improves filtration quality by having very low TSS in permeate. Figure 8 below shows permeate that was filtered out of a membrane thickening system. Another function of the diffuser is to provide aeration for continued biomass destruction.

Figure 7: Biofilm from a Submerged Flat Plate Membrane Thickening Unit

Figure 8: Permeate Collected From a Submerged Flat Plate Membrane Thickening Unit

Although this is a very unique thickening method it has many advantages such as being able to thicken reliably up to 4% solids concentration without the use of polymers in contrast to mechanical thickeners and attention to decanting or gravity thickening. Thickening with the membranes operates continuously and unattended twenty four hours a day (Bailey and Steinberg, 2005). Since there is no attention required for thickening this will result in reduced operation and maintenance costs in contrast with a mechanical thickener which can be quite labor intensive. Another advantage that is very unique to this method, is it produces a reuse quality permeate which can be recycled to the head of the plant or sent directly to disinfection. Permeate filtered out of a membrane thickener features very minimal total N and P concentration, because it is collected in the tank that houses the SMU which is aerated therefore does not create an anaerobic zone. This does not allow PAO bacteria to release phosphorus in the liquid stream in contrast with other thickeners such as gravity thickeners and decanting utilized with an aerobic digestion system.

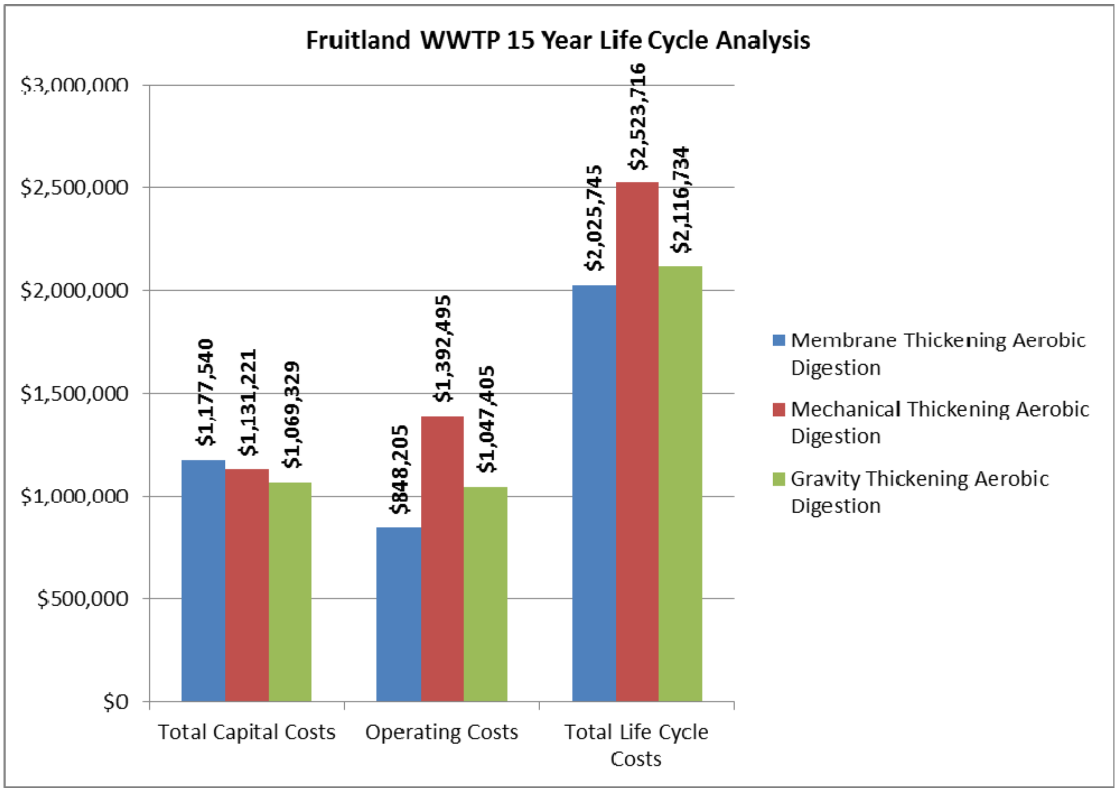
Membrane thickening however does have disadvantages. First the sludge must be screened to a minimum of 2 mm in order to protect the integrity of the equipment. Note the secondary sludge flow is not a large portion of the overall flow therefore the screening equipment is small in comparison with the screening at the head works. Secondly this thickening method can only handle WAS or secondary sludge. Since PS is very rich in readily biodegradable material biological fouling can occur very quickly with the membranes. Although thickening with membranes does not require any attention, this is a somewhat new approach so wastewater treatment operators can be intimidated by the technology.

The main disadvantage with membrane thickening is it is a high capital cost alternative in comparison to gravity, mechanical, and decant thickening alternatives which for most WWTPs is the most important factor on the selection of a technology. Membrane thickening does have very high capital cost in comparison to other alternatives but surprising to note that they may have the lowest overall costs that include operating and capital cost over a 15 to 20 year life cycle which is the typical design life of a wastewater treatment facility. Fruitland WWTP in Fruitland, Maryland is currently operating as at 0.5 MGD but will upgrade to a design flow of 0.8 MGD. The upgrade to 0.8 MGD for this plant will include converting their current biological liquid treatment process into an enhanced nutrient removal (ENR) process and upgrade the solids handling facility. The consulting engineer for this facility George, Miles, & Buhr (GMB) Engineers analyzed the cost and benefits for three pre-thickened aerobic digestion systems for the Fruitland WWTP. The three technologies evaluated were aerobic digestion utilizing mechanical thickening, membrane thickening, and gravity thickening (GMB Engineers, 2012). Table 3 and Figure 9 below shows and compares the capital and operating cost comparisons of the three solids handling technologies considered for the Fruitland WWTP.

Table 3: Life Cycle Cost Comparisons of Aerobic Digestion Technologies for Fruitland WWTP (Fruitland WWTP Business Case, GMB Engineers 2012)

Membrane Thickening Aerobic Digestion				
Item	**Unit**	**Quantity**	**Unit Cost**	**Total Cost**
Equipment Costs	Lump Sum	1	$930,000	$930,000
Concrete for Additional Tanks	Cubic Yard	125	$250	$31,250
Gravel Below Tanks	Cubic Yard	55	$35	$1,925
Electrical	--	--	--	$65,100
Piping	--	--	--	$149,265
Total Capital Costs	--	--	--	**$1,177,540**
Operating Costs	Year	15	$56,547	**$848,205**
Total Life Cycle Costs	--	--	--	**$2,025,745**
Mechanical Thickening Aerobic Digestion				
Item	**Unit**	**Quantity**	**Unit Cost**	**Total Cost**
Equipment Costs	Lump Sum	1	$885,600	$885,600
Electrical	--	--	--	$171,029
Piping	--	--	--	$74,592
Total Capital Costs	--	--	--	**$1,131,221**
Operating Costs	Year	15	$92,833	**$1,392,495**
Total Life Cycle Costs	--	--	--	**$2,523,716**
Gravity Thickening Aerobic Digestion				
Item	**Unit**	**Quantity**	**Unit Cost**	**Total Cost**
Equipment Costs	Lump Sum	1	$813,400	$813,400
Concrete for Additional Tanks	Cubic Yard	262	$250	$65,500
Gravel Below Tanks	Cubic Yard	84	$35	$2,940
Electrical	--	--	--	$130,551
Piping	--	--	--	$56,938
Total Capital Costs	--	--	--	**$1,069,329**
Operating Costs	Year	15	$69,827	**$1,047,405**
Total Life Cycle Costs	--	--	--	**$2,116,734**

Figure 9: Fruitland WWTP Aerobic Digestion Alternatives Life Cycle Costs



As seen in both Table 3 and Figure 9 that although membrane thickening has higher capital costs than mechanical and gravity thickening aerobic digestion systems at $1,177,450 it has the lowest overall total costs over a 15 year life cycle at $2,025,745. Membrane thickening has 40% and 19% less operating cost compared with mechanical and gravity thickening respectively.

Adding a thickening element to an aerobic digestion system provides substantial economical and process advantages. There are several process benefits by incorporating thickening to an aerobic digestion system. One benefit is Class B stabilization can be achieved in a reduced tank volume. Another is the ability to retain heat in colder climates resulting in improved volatile solids reduction. Since the burning of volatile solids in an aerobic digestion process is an exothermic reaction where it provides heat to the surround system therefore it is more resistant to colder climates. Another notable benefit to thickening is the ability to increase sludge storage capacity in existing tanks.

As shown in the Fruitland WWTP case study the advantages of sludge thickening in aerobic digestion systems provides substantial economic benefits. Although this was demonstrated in the example above, this discussion will provide a more detailed outline of the specific advantages and resulting economic benefits. In addition, actual operating data from plants with pre-thickened aerobic digestion systems will be examined. Thickening reduces the volume of the sludge to be processes resulting in smaller process tank volumes resulting in lower concrete construction costs. WAS thickening is a common method for reducing the volume in aerobic digesters (Turovskiy, 2001). Thickening reduces air requirements that results in lower energy costs since the volume of solids to be processed is much smaller than if the sludge was not thickened. In a digester processing WAS less than 2.0% solids the mixing air is greater than the process air demand and consequently most of the air put into the digester is essentially wasted. By thickening the sludge the volume of the tanks are reduced and thus the mixing air is also reduced. In digesters with thickened solids around 3.0% the process air demand is usually close to the mixing air demand which brings the process and mixing air closer in value preventing air from being wasted for non-biological purposes (Bailey and Steinberg, 2005).

GMB Engineers also evaluated the current aerobic digestion system at the Fruitland WWTP with a pre-thickened aerobic digestion system. The current aerobic digestion process at Fruitland WWTP does not implement any pre-thickening and solids leave the aerobic digestion process at 1.5% solids. Under this operation the downstream thickening and dewatering units will be heavily loaded and undersized to handle increased plant flows. Sludge minimization in the existing aerobic digestion system is minimal at 10% VS destruction in comparison to thickening the sludge to 3% solids concentration results in 42% VS destruction. By utilizing a pre-thickened aerobic digestion system GMB Engineers estimated Fruitland WWTP would save approximately $66,000 in annual operating costs which includes costs associated with disposal, electrical, chemicals, and labor (GMB Engineers, 2012).

As mentioned in the GMB Business Case Study for Fruitland WWTP, thickening helps to reduce and improve efficiency of dewatering operations by reducing volumetric and solids loading to these systems. Providing better thickening directly results in improved volatile solids destruction and SRT. Improved SRT decreases the frequency of dewatering equipment which will in turn lower polymer usage and costs. With better volatile solids reduction less solids are sent to dewatering equipment reducing the quantity of total solids to be dewatered. An example of this is described at the Union Rome WWWTP in Union Rome, Ohio which operates an aerobic digestion system that incorporates membrane thickening. Prior to incorporation of the membrane thickening aerobic digestion system the Union Rome facility operated their belt press five days a week (260 days per year). Improved thickening achieved with the membrane thickening aerobic digestion process substantially increased the capacity of the Union Rome facility, resulting in reduced belt filter press operations and decreasing the frequency of the sludge to be dewatered. The membrane thickening aerobic digestion process reduced the belt filter press operations at the Union Rome WWTP to three days every two and a half months (15 days per year). The Union Rome facility has increased their belt press efficiency by using 40% less polymer to dewater the same amount of solids as the previous sludge handling process and reduced the quantity of sludge hauled to the landfill by more than 50%. This results in savings over $58,000 in hauling costs and over $3,000 in polymer costs annually since operating the membrane thickening aerobic digestion process (Woo, 2012).

Another example of a pre-thickening aerobic digestion process improving dewatering operations is seen at McFarland Creek WWTP in Chargin Falls, Ohio. Since 2005 McFarland Creek WWTP currently operates an aerobic digestion system utilizing membrane pre-thickening and prior to this system was operating a conventional aerobic digestion system. The pre-thickened aerobic digestion system has shown improvement in thickening from 2% to 4% solids concentration. This improvement in thickening resulted in a 41% reduction on both solids disposal and polymer costs compared to their previous aerobic digestion system at this facility. Also important to note that the membrane thickening process was retrofitted into existing tanks and improved thickening performance resulted in increased SRT resulting in Class B treatment which the previous system was not capable of. By having the option of land applying instead of disposal at a landfill which was done previously resulted in a 20% cost reduction (Bailey and Mendez, 2007).

Finally thickening greatly helps reduce the mass and volume solids to be disposed particularly for applications where there is no dewatering process and the sludge is liquid hauled to another facility for further processing or disposed at a landfill. Disposal of wastewater sludge to landfills or other facilities for further processing can be expensive because of fuel costs and tipping fees. For example, from January 2006 to February 2008 Woodside WWTP in Suffolk County, New York was hauling an annual average of 1,110,00 gallons of liquid sludge to be processed at Bergen Point a centralized wastewater treatment facility. Suffolk County paid more than $100,000 annually to haul this sludge from Woodside WWTP to the Bergen Point facility. This was a substantial cost to Suffolk County and were looking for a solids handling process to minimize liquid hauling costs from Woodside WWTP.

Woodside WWTP installed a Membrane Thickening (MBT) process in order reduce hauling costs at this facility. The MBT process at Woodside WWTP pre-thickens liquid sludge produced at this facility up to 3.5% solids concentration. By pre-thickening the sludge up to 3.5% solids concentration sludge hauling at Woodside WWTP was a reduced by more than 57% which resulted in an annual savings of $60,000 on hauling costs (Treatment Plant Operator, 2012).

Nutrient Removal Using Aerobic and Anoxic Control

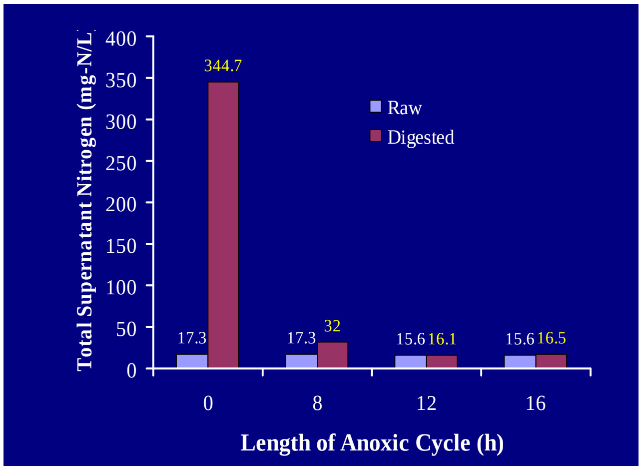
Nutrient pollution creates many water quality issues. Discharge of wastewater containing excessive amounts of N and P into lakes, reservoirs, rivers, and streams can result in a surplus of plant growth. This growth causes a depletion of dissolved oxygen in the water, sufficiently harming fishery resources. Excessive algal growth can also create distasteful drinking water. Nutrients can accumulate over time in sediments of lakes and reservoirs and ultimately recycle back, posing a long term water quality problem that is difficult to manage. It has been established that, for controlling excessive algae growth in water bodies, the phosphorus concentration has to be kept lower than 0.03 mg/L (Gachter and Imboden, 1985).

The total kjeldahl nitrogen (TKN) is the sum of organic nitrogen, ammonia, and ammonium. Ammonia is toxic to plant and animal life and depletes dissolved oxygen in water. Toxicity to fish in freshwater has been observed at low concentrations of 0.068 to 2.0 mg/L of ammonia, depending on species, temperature, and pH. At much lower concentrations, aquatic life become less active affecting migration, feeding, and reproduction (Parker, 2012). In fact it was found that the growth rate of mussels in the St Croix River was substantially reduced at ammonia concentrations as low as 31 µg/L of ammonia (Newton, 2002).

Due to these concerns with N and P pollution, many regulatory agencies are in the process of or have already adopted nutrient management plans. In fact wastewater treatment facilities in the state of Massachusetts must comply with an effluent discharge limit for 0.1 mg/L of total P and 5 mg/L of total N.

An aerobic digestion process has the capability of creating aerobic, anaerobic, and anoxic zones to facilitate the nitrification and denitrification processes. This is required to biologically achieve total nitrogen removal and can be accomplished by cycling the air on and off in process tanks, having separate anaerobic or anoxic tanks, and controlling air flow through oxidation reduction potential (ORP) or pH. Figure 10 below shows the effect an anoxic cycle has on total N in dewatering filtrate.

Figure 10. Effect of Anoxic Cycle on Total N in Dewatering Filtrate (Al-Ghusain, Hamoda, El-Ghany, 2002)



Phosphorus removal in biological processes including aerobic digestion systems presents a much more challenging, complex, and sophisticated concept in contrast to nitrogen removal. In order to understand these concepts it is important to note that phosphorus is comprised of the following three forms: inorganic phosphorus, polyphosphorus, and organic phosphorus (Ju, Porteous, and Shah, 2005).

Although phosphorus is generally not soluble in water, aqueous phosphates are commonly found in wastewater. Under acidic conditions H^+ ions are present phosphate (PO_4^{-3}) can be transformed into aqueous forms of hydrogen phosphate (HPO_4^{-2}), dihydrogen phosphate (H_2PO_4), and phosphoric acid (H_3PO_4). The dissolution of inorganic phosphorus is controlled by pH and described using the acid disassociation equilibrium constant (pK_a). Phosphoric acid is triprotic therefore the pKa values of hydrogen phosphate, dihydrogen phosphate, and phosphoric acid are 12.7, 7.2, and 2.12 respectively. Under pH conditions between 12.7 and 7.2 hydrogen phosphate and dihydrogen phosphate species are most present which can form bonds with minerals such as calcium, sodium, and magnesium. The bonds formed with these minerals and aqueous phosphate species form precipitates which remove phosphorus in solution and remain in the solids. Under acidic conditions phosphoric acid is the dominant species and cannot form bonds with minerals or metals so the phosphorus stays in aqueous form. With aerobic and anoxic control nitrification and denitrification sequencing is possible and results in excellent pH control, preventing the dissolution of inorganic phosphorus by maintaining the pH to range between 6.5 to 7.4. Dissolution of inorganic phosphorus precipitates is controlled by physical and chemical conditions, with pH being the most important. Lowering the pH between 4 and 6 clearly promotes the release of inorganic phosphorus (Ju, Porteous, and Shah, 2005).

Polyphosphorus accumulating organisms (PAOs) can store carbon compounds as a source of energy in the absence of oxygen or nitrate, which are common energy sources in biological processes. The storage of carbon compounds by PAOs results in a polyphosphorus release. By having a separate anoxic zone in addition to the aerated aerobic digester tanks the incoming WAS into an anoxic tank provides a fresh carbon source for PAOs to release polyphosphate following the exhaustion of nitrate which also occurs in this tank. The aerated aerobic digester tank(s), allows for the PAOs to grow and uptake the released polyphosphorus while their stored carbon reserves are oxidized resulting in the phosphorus remaining in the solids and removed in solution. This uptake of the polyphosphate by PAO bacteria under aerobic conditions results in the polyphosphorus to remain in the solids, resulting in substantially reduced phosphorus levels in permeate from an aerobic digestion process with membrane thickening. Sludge shows clear cycles of significant phosphorus release under no aeration and subsequent phosphorus uptake when aeration is turned back on, consistent with the commonly accepted metabolism of PAO microorganisms (Ju, Porteous, and Shah, 2005). The growth rate of biomass under anoxic conditions is about 40% lower as compared to the growth rate of biomass under aerobic conditions, so PAOs are capable of facilitating the removal of large amounts of phosphorus in the liquid phase because growth rate is significantly increased under aerobic conditions (Van Haandel & Van der Lubbe, 2007).

Due to substantial biomass destruction in aerobic digestion process, PAO decay occurs making organic phosphorus release unavoidable. When PAO decay the organic phosphorus is released into the liquid phase. Table 4 below summarizes the values of some key characteristics of PAO as compared to those of conventional micro-organisms in activated sludge systems.

Table 4: Parameters of PAO compared to regular heterotrophic organisms at 20°C, (Van Haandel and Van der Lubbe, 2007)

Parameter	**PAO**	**Non-PAO**	**U of M**
Polyphosphorus Content	0.38	0.025	mg P .mg^{-1} VSS
Decay Constant	0.04	0.24	d^{-1}
Endogenous Residue	0.25	0.20	(-)
P-fraction end..residue	0.025	0.025	mg P .mg^{-1} X_e
Ratio VSS/TSS	0.46	0.80	mg VSS .mg^{-1} TSS
Denitrifying fraction	0.6 – 1.0	1.0	(-)
Denitrification rate	0.10/0.08	0.10/0.08	mg N .mg^{-1} X_a.d^{-1}
Anaer. Phosphate release	0.5	---	mg P .mg^{-1} COD

Analyzing T able 4 above, it illustrates that the decay rate of a PAO is approximately six times slower than non-PAO bacteria, and there are approximately twice as many non-PAO bacteria than PAO in a typical biomass. Although non-PAO bacteria are more common in a biomass and have a faster decay rate they contain approximately fifteen times less polyphosphorus than PAO bacteria. These observations show that the PAO in biomass does not decay at a fast enough rate and there is not a sufficient amount of polyphosphorus content in non-PAO bacteria for a significant amount of organic phosphorus release to occur in the liquid phase. It can be concluded that organic phosphorus release in permeate produced from an aerobic digestion process with membrane thickening will be very minimal even though it is unavoidable due to PAO decay from substantial volatile solids destruction in this process.

An aerobic digestion process is capable of minimizing the release of the three forms of phosphorus discussed above. The main function of utilizing aerobic and anoxic control in both liquid treatment and solids handling processes at a wastewater treatment plant is to provide removal of nutrients specifically nitrogen (N) and phosphorus (P). One of the key advantages to aerobic digestion processes is that it features reduced nutrients specifically nitrogen (N) and phosphorus (P) in side streams. A side stream is any process flow resulting from the treatment of biosolids that flows back to the liquid treatment process. Examples of side streams are filtrate or centrate from dewatering operations and supernatant from digestion processes. High nutrient concentrations in side streams from a solids handling process are widely recognized as a leading cause for high N and P in plant effluents of biological nutrient removal (BNR) facilities. At a wastewater treatment plant side stream flow accounts for approximately 15% to 20% of the total influent nitrogen load and 20% to 30% of influent phosphorus (Bilyk, Taylor, Pitt, and Wankmuller 2011). Filtrate from dewatering anaerobic digested sludge at the Marshall Street Water Reclamation Facility (WRF) in Clearwater, FL contains 51 mg/L of total P which contributes to 30% of the total influent P loading (US EPA 2008). Nutrients in side stream flow with subsequent recycling to a plant's head works would defeat the purpose of a BNR liquid treatment process.

In contrast to an aerobic digestion system an anaerobic digestion system does not have an aerobic zone. In an anaerobic digestion process readily biodegradable organics are fermented into Volatile Fatty Acids (VFAs) that promote PAO to release P. The absence of an aerobic zone in an anaerobic digestion process prevents the oxidization of ammonia into nitrates and the PAO cannot uptake the P released. As a result anaerobic digestion side streams are rich total N and P. Ammonia concentrations in dewatering side streams from anaerobic digestion processes can range from 900 to 1,500 mg/L as nitrogen (N) or more which can increase the ammonia concentration in the plant effluent by 3 to 5 mg/L on an average day basis (Barnard, Kobylinski, Phillips, Wallis-Lange, 2006). Table 5 below shows concentrations of N and P that is typically found in anaerobic digester side streams while Table 6 below shows typical the N and P concentrations found in aerobic digestion side streams.

Table 5: Anaerobic Digester Supernatant Characteristics (EPA Sludge Treatment and Disposal Design Manual, 1979)

Parameter*	Range of Plant Averages (mg/L)
Suspended Solids	143 – 2,205
Total Kjeldahl Nitrogen	306 – 1,144
NH_3-N	253 – 853
Total PO_4-P	63 – 143

Table 6: Aerobic Digester Supernatant Characteristics (Water Environmental Federation, 1995)

Parameter*	Range (mg/L)	Typical Value (mg/L)
Suspended Solids	46 – 11,500	3,400
Total Kjeldahl Nitrogen	10 – 400	170
Total Phosphorus	19 – 241	100
Total Dissolved Phosphorus	2.5 – 64	25

*pH range 5.9 – 7.7

There are economic benefits to having aerobic and anoxic control in an aerobic digestion system because it allows for N and P to be removed biologically minimizing or eliminating chemical addition in the liquid treatment process. Since aerobic digestion systems feature reduced N and P in side stream flow it will protect the effluent quality of the liquid treatment process when recycled to the head works of the plant where there is minimal or no chemical addition required. Chemical addition to remove P and N in order to meet effluent discharge requirements can be expensive depending on the required dosage to comply with effluent discharge requirements, and can also increase sludge loads. Alum and ferric are chemicals commonly used to remove P and methanol or Micro-C are commonly added as a carbon source to aid in the denitrification process to achieve total N removal. Chemical addition for BNR removal can increase sludge loads up to 40% (Lenntech, 2009). For example, Western Branch WWTP in Upper Marlboro, Maryland must currently meet a National Pollutant Discharge Elimination System (NPDES) permit of 1 mg/L for total P and 3 mg/L for total N based on a monthly average. Western Branch WWTP operates a high rate activated sludge liquid treatment process to achieve biological nitrogen removal, however all P removal is done by chemical addition using alum which has an annual capital cost of $107,000. While total nitrogen removal is done biologically at this facility methanol is added to facilitate the denitrfication process for total N removal. The annual cost of methanol addition at this plant was $425,000. The addition of alum and methanol resulted in a $32,400 and $372,000 increase respectively in disposal cost (US EPA, 2008).

An example of a facility that utilizes the anoxic and aerobic operation is Dundee WWTP in Dundee, Michigan. Since 2005, Dundee WWTP operates a membrane pre-thickened aerobic digestion process which consists of two aerobic digestion tanks and one membrane thickening basin. Blowers are on during nitrification and off during dentirification in the aerobic digestion tanks. From 2005 to 2007, the permeate quality extracted from the membranes from this process has very low total suspended solids (less than 2 mg/L), total ammonia as nitrogen (less than 0.12 mg/L), nitrate as nitrogen (less than 3 mg/L), and total P (less than 7 mg/L). Due to the outstanding permeate quality produced from this process it is sent directly to disinfection eliminating an additional load to the head works of the plant (Bailey and Mendez, 2007).

In addition, Union Rome WWWTP in Union Rome, Ohio which operates an aerobic digestion system that incorporates membrane thickening since 2009. The Union Rome WWTP aerobic digestion system consists of one aerobic digestion tank, one membrane thickening basin, and one anoxic tank. This arrangement was utilized to reduce ammonia and during the entire operations the permeate extracted from this system contains less than 0.1 mg/L of ammonia as N and less than 5 mg/L of total P (Woo, 2012).

The permeate characteristics of the Dundee WWTP and Union Rome WWTP aerobic digestion systems are below the typical supernatant characteristics for total N and P of aerobic digesters outlined in Table 5.

Temperature Control

Temperature control is absolutely critical to the sustainability and performance of an aerobic digestion system because microorganisms are very sensitive to temperature conditions. Temperature control ensures a healthy biomass. As with all biological processes, the higher the temperature, the higher the efficiency. At temperatures less than 10 °C (50 °F), an aerobic digestion process is basically ineffective (Water Environment Federation, 2007). Volatile solids destruction and microbial activity are temperature dependent. The higher the temperature the better the volatile solids destruction and lower temperatures yield less volatile solids reduction due to faster microbial activity rates at higher temperatures. When the temperature drops to 10°C or lower, biological activity is severely reduced and volatile solids reductions of as low as 20% are normal (Enviroquip, 2000).

Nitrification is dependent on dissolved oxygen levels but is also temperature dependent. Nitrification is known as the most temperature-sensitive step among the biological processes in wastewater treatment (Hwang and Oleszkiewicz, 2007). Nitrification can occur under low temperature conditions as long as there is adequate dissolved oxygen. Xie, Wang, and Zhang studied temperature effects on aerobic dentirification and nitrification and determined nitrification rates remain high even with a temperature drop from 15^{o}C to 5^{o}C under DO conditions as low as 1.4 mg/L (Xie, Wang, Zhang, 2003). Since aerobic digestion is operated under low DO conditions this principal does not apply. Nitrosomonas and Nitrobacter bacteria drive the nitrification process are temperature sensitive and will die at temperatures exceeding 49 °C (Oerke, 2010).

One of the disadvantages to an aerobic digestion system is it is ineffective in cold temperature climates. While this is generally accepted there are methods that can be utilized to improve performance with regard to temperature. To achieve optimum digester performance, temperatures should be maintained between 20°C and 35°C year-round (Enviroquip, 2000). As discussed previously thickening in general provides resistance to colder climates because the heat generated from volatile solids destruction is kept in a more concentrated area containing less water volume. In addition aerobic digestion tanks can be covered to optimize temperatures and performance in colder climates. Since 2009 Frackville WWWTP in Frackville, Pennsylvania operates a conventional aerobic digestion process with covered process tanks. Prior to this process the aerobic digestion tanks were not covered. The covered aid in temperature control resulting in better digestion observed from a more than two and a half times more reduction in solids from having uncovered process tanks. A $15,000 annual savings in solids disposal resulted from the reduction of solids with improved temperature control (Cleary and Woo, 2013).

Bellefonte WWTP in Bellefonte, Pennsylvania operates a mechanical thickened aerobic digestion process. The aerobic digester tanks are also covered. Bellefonte WWTP uses thickening and aerobic digestion tank covers to control temperatures during winter operations. With average ambient temperatures in Bellefonte, Pennsylvania reaching as low as minus 3°C during the 2010 operations, the aerobic digesters were able to sustain average temperatures no lower than 17°C from this period. Excellent VSR is achieved at the Bellefonte facility due to longer SRT, complimented by outstanding temperature control maintained in the aerobic digester tanks as noted above. As shown in Figure 3 below, a VSR of 40% to 59% was achieved from December 2009 to January 2011 at this facility. This performance exceeds the minimum CFR 40 Part 503 Class B Vector Attraction regulations of a minimum 38% volatile solids reduction (Thompson and Woo, 2012). Figure 11 below shows temperature data and Figure 12 shows volatile solids reduction results at Bellefonte WWTP.

Figure 11: Temperate Data at Bellefonte WWTP

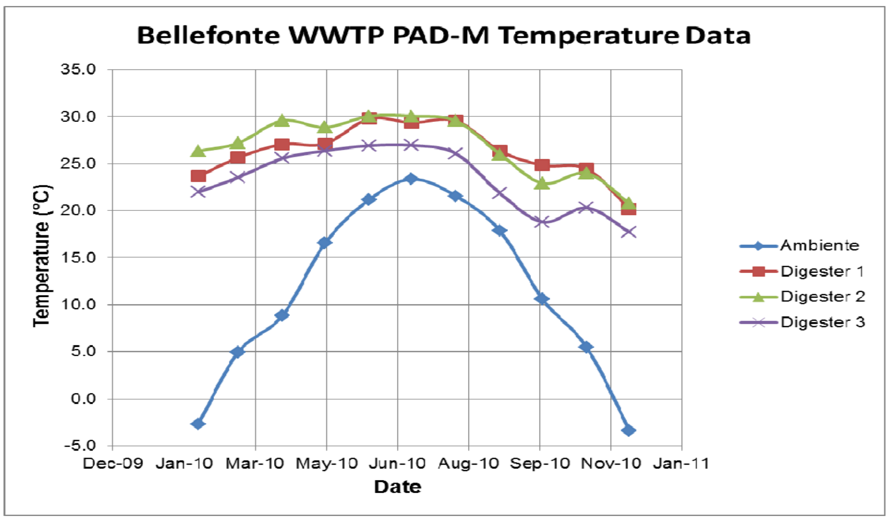
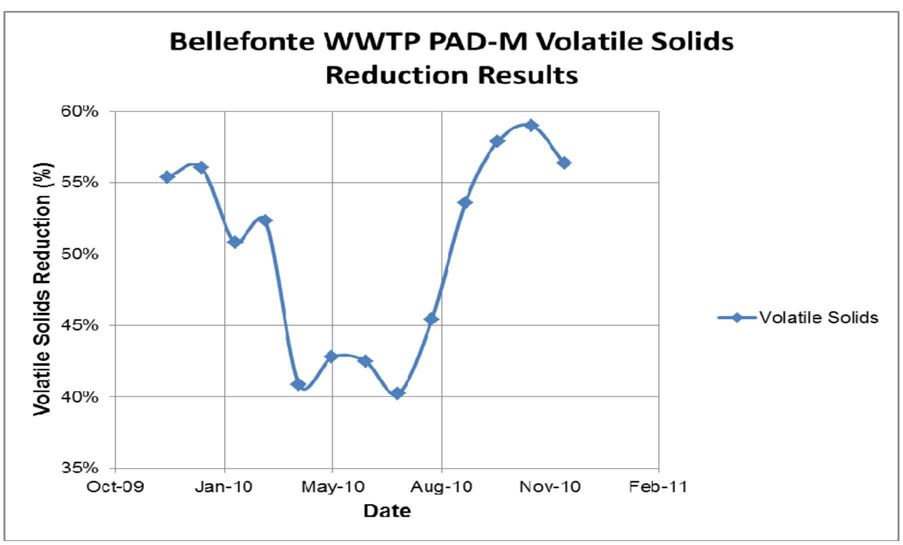


Figure 12: Volatile Solids Reduction Data at Bellefonte WWTP



Aerobic Digestion Operational Flexibility and Process Control

Having operational flexibility and process control can help enhance aerobic digestion performance. As mentioned in previous sections in this research microbial activity is much faster in warmer temperature conditions, therefore air flow requirements will also vary depending on the time of the year. It can be very possible that air flow requirements will be substantially lower during winter operations then summer operations. Also microbial activity occurs mostly in the beginning phases of the process, so air flow requirements also vary from tank to tank. In order to reduce energy requirements blowers should be put on variable frequency drives (VFD) so a wider range of air flow can be supplied for seasonal and tank variances.

Piping modifications can also help add operational flexibility to aerobic digestion systems. For a pre-thickened system that is in an area where warm temperatures can be extreme for an extended period of time, to avoid thermophilic conditions a pipe to bypass thickening operations is helpful. This will aid in reducing temperatures in process tanks by thinning the sludge and will also reduce air flow requirements, increase oxygen transfer and mixing efficiencies of the aeration system. Also adding piping for the system to be capable of feeding sludge into any of the digesters can be helpful in the event one or more of the digesters has depressed DO levels the other digesters can switch functions as the first stage digester.

To help gauge and monitor performance it is recommended aerobic digestion systems be equipped instrumentation that can monitor TSS, pH, temperature, and DO. This will provide readily accessible data and necessary adjustments to the process to improve performance can be done rapidly. For example if the pH is low in the digesters then the adjustment that needs to be made is to turn off air flow to the tank and if the pH is too high then the blower can be sped up to provide more air to the system. In addition DO, Oxygen Reduction Potential (ORP), and pH instrumentation can be used in integrated with VFDs to control how much air blowers will supply in an aerobic digestion system. Operators can set DO control points for the blowers to turn off when the DO reaches more than 2 mg/L and increase blower speed at DO conditions less than 0.5 mg/L. Not only does this level of controls provide reduced energy but also reduced operator attention as well as increased efficiency. To create aerobic and anoxic conditions at Dundee WWTP the air is cycled on and off in the aerobic digester tanks with the aid of ORP blower controls (Bailey and Mendez, 2007).

If not properly operated and monitored many issues may occur when operating an aerobic digestion system. For a controlled aerobic digestion system careful consideration must be given to all of the following parameters:

Dissolved Oxygen: When thickened sludge is fed to the aerobic digester the oxygen uptake rate in the digester is extremely high, with as much as 70% of the total oxygen requirement needed in the first 10 days.

Nitrification-Denitrification and pH and Alkalinity Control: Sufficient oxygen must be provided to achieve nitrification of the sludge. As sludge nitrifies it creates acid and if nitrification is allowed to proceed unchecked, then a pH and alkalinity drop will occur in the digester and upset conditions will occur. Alkalinity and pH can be stabilized by adding chemicals to the wastewater such as lime for immediate results if required.

Temperature: When the temperature drops to 10°C or lower, biological activity is severely reduced and volatile solids reductions of as low as 20% are the norm. Above 37°C nitrification will be inhibited due to the adverse effects of high temperature on nitrifying bacteria. Where summer temperatures are high the sludge should be diluted in order to cool the system.

Foaming: High loading of sludge in the aerobic digester system during warm climates, turnover of bacteria population in the spring and fall, and filamentous microorganisms result in foaming problems. Control methods that can be used for foaming are too thin or dilute the sludge to cool the aerobic digester to maintain mesophilic operations or to add chemicals such as chlorine defoamers to destroy the filamentous bacteria.

Odor: Odor problems should not occur when operating the aerobic digester system. Control methods for odor are to thin the sludge so that it is less viscous and oxygen can be transferred more efficiently to maintain sufficient dissolved oxygen during aeration, shorten the air off cycle, and balance air in the digester properly.

Table 7: Aerobic Digestion Operating Remedies to Common Issues

PROBLEM	ACTION
pH > 7.2	1. Increase airflow 2. If air is all the way up, thin or dilute the sludge to increase the oxygen transfer efficiency in the sludge
pH < 6.5	1. Turn air off 2. Resume air operation by cycling the air on and off 3. If possible, regulate airflow to maintain conditions for simultaneous nitrification and denitrification 4. If no other result or pH severly depressed (<5.0) add chemicals to the wastewater such as lime
Temperature > 35°C	1. Thin or dilute the sludge in order to cool the system
Alkalinity < 100 mg/L $CaCO_3$	1. Add chemicals to the wastewater such as lime (nitrification cannot occur without sufficient alkalinity)
Ammonia > 40 mg/L	1. Increase airflow 2. If air is all the way up, thin or dilute the sludge to increase the oxygen transfer efficiency in the sludge
Nitrates > 10 mg/L	1. Turn air off 2. Resume air operation by cycling the air on and off 3. If possible, regulate airflow to maintain conditions for simultaneous nitrification and denitrification 4. If no other result or pH severly depressed (<5.0) add chemicals to the wastewater such as lime

Aeration in an Aerobic Digestion Process

Much has been discussed about optimization techniques for aerobic digestion processes but another aspect just as important to the sustainability of this system is to ensure adequate mixing and aeration. Proper operation of an aerobic digestion system requires adequate mixing because the introduction of oxygen to maintain a biological process typically provides a mixing action, these parameters are interrelated (Water Environment Federation, 2005). The mixing and aeration system is the heart of an aerobic digestion process. Microorganisms in this process rely on oxygen to metabolize organic matter and if oxygen is not sufficiently transferred to them the process will not operate efficiently. All the optimization techniques discussed above can be implemented in an aerobic digestion system but if the sludge is not adequately mixed and aerated the process will be highly ineffective. This holds especially true if an aerobic digestion system is pre-thickening sludge prior to digestion. The thicker and more viscous the sludge more difficult it will be to adequately mix therefore transferring oxygen to the microorganisms will be less efficient.

According to Environmental Dynamics International, that when developing aeration system design it is necessary to have sufficient data to allow the many factors to be properly evaluated. Some of these factors that must be considered are listed below (Environmental Dynamics, 2012).

1. Depth of process tank
2. Type of diffuser efficiency: fine, medium, or coarse bubble
3. Geometry of diffusers in process tank
4. Energy level in the aeration basin (horsepower/1,000 ft^2)
5. Organic load to the reactor: type of waste, concentration (mg/L), and total mass load in pounds per day or kilograms per day
6. Process to be supported by the aeration (i.e. extended aeration, sludge holding tank, aerobic digester, activated sludge, etc.)
7. Site elevation
8. Wastewater temperature
9. Submergence depth of the diffuser
10. Dissolve oxygen concentration to be maintained in the bioreactor

Based on the stoichiometric equations listed in Table 1 the oxygen required for microbial activity can be calculated. Taking the stoichiometric equation for aerobic digestion with complete nitrification-denitrification the theoretical oxygen demand for this process is calculated as follows:

Molecular Weight of Biomass ($C_5H_7NO_2$) = 113 g/mol
Molecular Weight of Oxygen (O_2) = 32 g/mol

$$1 lb Biomass\, x \frac{1kg}{2.2lb} x \frac{1,000g}{kg} x \frac{1mol}{113g} x \frac{7 mol O_2}{1 mol Biomass} x \frac{32g}{mol} x \frac{1kg}{1,000g} x \frac{2.2lb}{kg} = 1.98 lb\, O_2$$

The above calculation yields an oxygen demand of approximately 2 lb Oxygen per lb of Biomass destroyed which includes the air requirements to achieve complete nitrification-denitrification process. This oxygen demand needs to be considered when designing an aerobic digestion system.

Coarse or fine bubble diffusers are generally used to transfer oxygen to the microorganisms in an aerobic digestion system. It is important to determine how much oxygen is required from the diffuser equipment. For biological processes such as an aerobic digestion process there are two oxygen demand requirements that must be considered, and they are actual oxygen requirement (AOR) and standard oxygen requirement (SOR). The AOR and SOR are typically expressed in pounds of oxygen per day per unit volume. Since oxygen is a gas demands are dependent on factors such as elevation which dictate atmospheric pressure and temperature.

The SOR is based on standard temperature (20^{o} C) and pressure conditions (14.7 psia). Important to note that the SOR will always be greater than the SOR therefore aeration systems are always designed based on the SOR (Sanitaire, 1990).

Sanitaire a company with over forty years of experience manufacturing fine and coarse bubble diffusers has thousands of diffuser installations in the United States with applications ranging from biological liquid treatment process aeration tanks, sludge holding tanks, and aerobic digestion tanks. Sanitaire has developed aeration design guidelines which have been widely accepted in the wastewater industry. Sanitaire's design guidelines provide rationale methods for calculating AOR of wastewater under specific site conditions and then converting the AOR into SOR. The formula that is widely accepted to convert SOR into AOR is as follows (Sanitare, 1990):

Equation 4: AOR to SOR Conversion Formula

$$AOR = SORx\alpha \left[\frac{\left(\beta \left(\frac{P_f}{P_S} \right) Csat_T - DO_f \right)}{Csat_{20}} \right] \theta^{T-20}$$

Where:

- AOR = Actual Oxygen Demand
- SOR = Standard Oxygen Demand
- α= Alpha Value which is the mass transfer coefficient ratio of wastewater to tap water. Typical accepted Alpha values range between 0.5 and 0.6 but can be as high as 0.7
- β = Beta Value which is the saturation correction factor used to correct for dissolved solids in wastewater. Typical accepted Beta value is 0.95
- P_f = Pressure at site conditions
- P_s = Pressure at standard conditions
- T = Temperature of wastewater

- $Csat_T$ = DO saturation at wastewater temperature and pressure at particular aeration equipment design submergence
- $Csat_{20}$ = DO saturation at standard temperature (20^o C) and pressure conditions (14.7 psia)
- θ = Temperature correction factor of the wastewater typically 1.024

Based Equation 4 above The AOR is based on factors that pertain to a particular site and in addition to site elevation and temperature is also dependent on the following (Sanitaire, 1990):

- Beta Value
- Alpha Value
- Dissolved Oxygen
- Oxygen saturation value for the aeration system at a specified submergence

The aeration equipment will transfer the oxygen to the bacteria in an aerobic digestion process but it will be blowers that will supply the air to the diffusers. The AOR to SOR ratio can also be determined by utilizing Equation 5 above. The AOR to SOR ratio is used to determine the airflow in standard cubic feet per minute that is required by the blower system. The airflow required for aerobic digestion is as follows:

Equation 5: Aerobic Digestion Airflow Requirements

$$Airflow = \frac{\dfrac{2lb\,O_2}{lbVS\ Destroyed} x \dfrac{lbVS\ Destroyed}{day}}{\gamma_{oxygen} x 0.2315 x OTE x (AOR:SOR) x \dfrac{1{,}440\min}{day}}$$

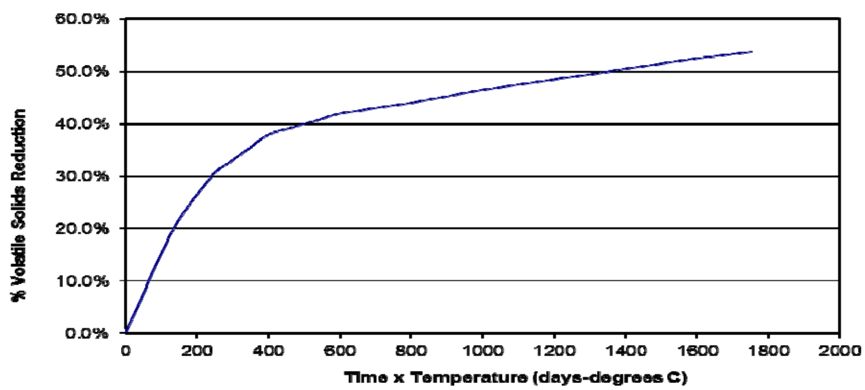
Where:

- Airflow = Air to be supplied to the diffuser system in standard cubic feet per minute (scfm)
- 2 lb O_2 per lb VS Destroyed = Air requirement by the biomass to destroy volatile solids
- γ_{oxygen} = specific weight of oxygen which is 0.076 lb per cubic foot
- 0.2315 = The percent of oxygen in the atmosphere by weight
- OTE = Oxygen Transfer Efficiency of the aeration system which is usually 0.75% per foot of submergence for coarse bubble diffusers and 2% per foot of submergence for fine bubble diffusers (Sanitaire, 1990)
- AOR:SOR = AOR to SOR ration determined in Equation 5

For the design of an aerobic digestion system the air requirements are based on two parameters air required for microbial activity to achieve volatile solids destruction which is expressed in Equation 6 above which is known as the process air, and air requirements for mixing is between 20 scfm per 1,000 cubic feet of volume and 40 scfm per 1,000 cubic feet of volume (Metcalf and Eddy, 1991). Since microbial activity mostly occurs in the first phases of the process, air requirements are almost always designed for the process air requirements in the first stage aerobic digestion tank. As seen in Figure 13 below volatile solids destruction is a function of time and temperature. The first ten days of digestion of WAS has a high oxygen uptake rate

(Turovskiy, 2001) and is also confirmed from Figure 13 below. Since most air required for the microbial process is achieved in the first phases of digestion, air requirements for subsequent aerobic digestion tanks are typically designed based on mixing air requirements.

Figure 13: Volatile Solids Reduction in an Aerobic Digester as a Function of Digester Liquid Temperature and Digester Sludge Age (Wastewater Engineering Treatment Disposal and Reuse, Third Edition, Metcalf and Eddy, 1991)



The Alpha Value Effect on Aerobic Digestion Process Performance

One of the process optimization techniques discussed in this research is the process advantages of pre-thickening. Pre-thickening, however can have unintended consequences in relation to aeration and mixing because the sludge will become more viscous making mixing progressively more difficult. Poor mixing results in the inability to properly distribute diffused oxygen to the microorganisms creating localized anaerobic conditions which cause foaming and odor problems. Independent German studies as well as testing data commissioned by Sanitaire and Redmon Engineering have shown that sludge with total solids concentrations greater than 20,000 mg/L are difficult to properly aerate and mix with diffused aeration alone (Redmon, Shaw, and Schoenenberger, 2003).

While it has been widely been accepted in the wastewater industry that aerating solids with total solids concentrations greater than 20,000 mg/L is very difficult as shown in the studies performed by Sanitaire, independent German studies, and Redmon Engineering (Redmon, Shaw, and Schoenberger, 2003), this research will confirm that aeration design is critical to the performance of the aerobic digestion system but also the importance of using the correct alpha value in aeration design is even more critical. If the correct alpha value is used in the aeration design aerobic digestion system performance is sustainable at total solids concentrations greater than 40,000 mg/L.

This study will examine the performance of two wastewater treatment plants that are both treating municipal wastewater, located in central Pennsylvania approximately 60 miles from each other so that temperature and site elevation differences are negligible, both aerobic digestion systems utilize gravity belt pre-thickening, the type of coarse bubble diffuser systems are identical, both systems were designed to achieve Class B biosolids stabilization. The primary difference between both facilities is the aeration systems were designed using different alpha values. The aeration system at one facility was designed for an alpha value of 0.55 while the other was designed for an alpha value of 0.72. The other difference is the 0.55 alpha facility operates two aerobic digester tanks in series while the 0.72 alpha facility operates three aerobic digester tanks in series.

The aerobic digestion process tanks at both facilities utilize Enviroquip's Airbeam® Cover aeration system shown in Figure 14 below. The Airbeam Cover is primarily used at both facilities for enhanced temperature control for improved VS destruction and physical odor control. The Airbeam® Cover aeration system is a flat panel aluminum cover that integrates a coarse bubble aeration system with hollow support beams supplying air to drop pipe coarse bubble diffusers with shear tubes. The shear tubes around each drop pipe diffuser creates an air lift pump mixing effect which increases the velocity of mixing allowing adequate aeration and mixing of highly concentrated solids.

Figure 14: Enviroquip's Airbeam® Cover Aeration System (Plan View on Left and Section View on Right)

These two facilities were selected in particular because not only are they similar in many ways but just using a different alpha value in the aeration design yielded very different performance results. Figure 15 through Figure 18 show pH, total solids, and volatile solids reduction data between the aerobic digestion system that utilized a 0.55 alpha value and the system that utilized a 0.72 alpha value.

Figure 15: Total Solids Comparison between 0.55 and 0.72 Alpha Value Facilities

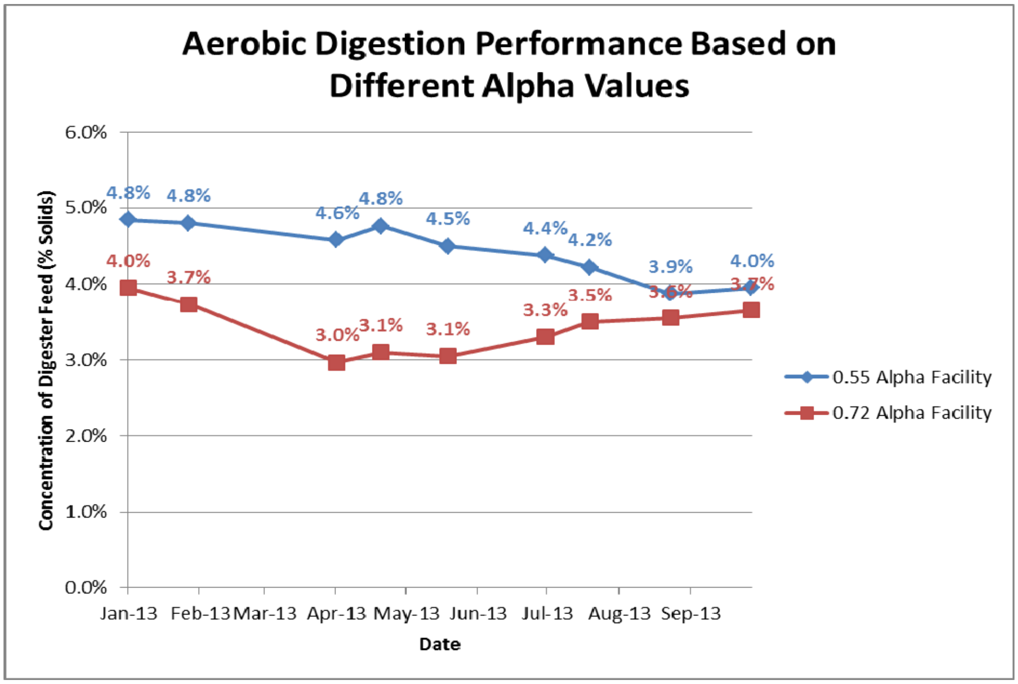


Figure 16: Volatile Solids Reduction Comparison between 0.55 and 0.72 Alpha Value Facilities

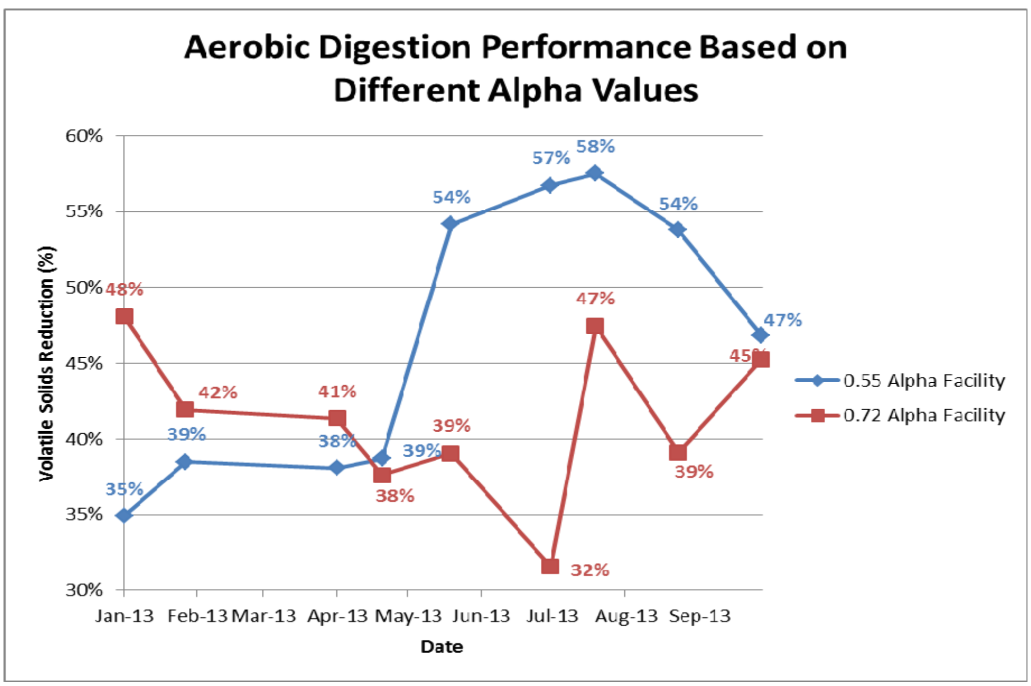


Figure 17: pH Data of 0.55 Alpha Value Facility

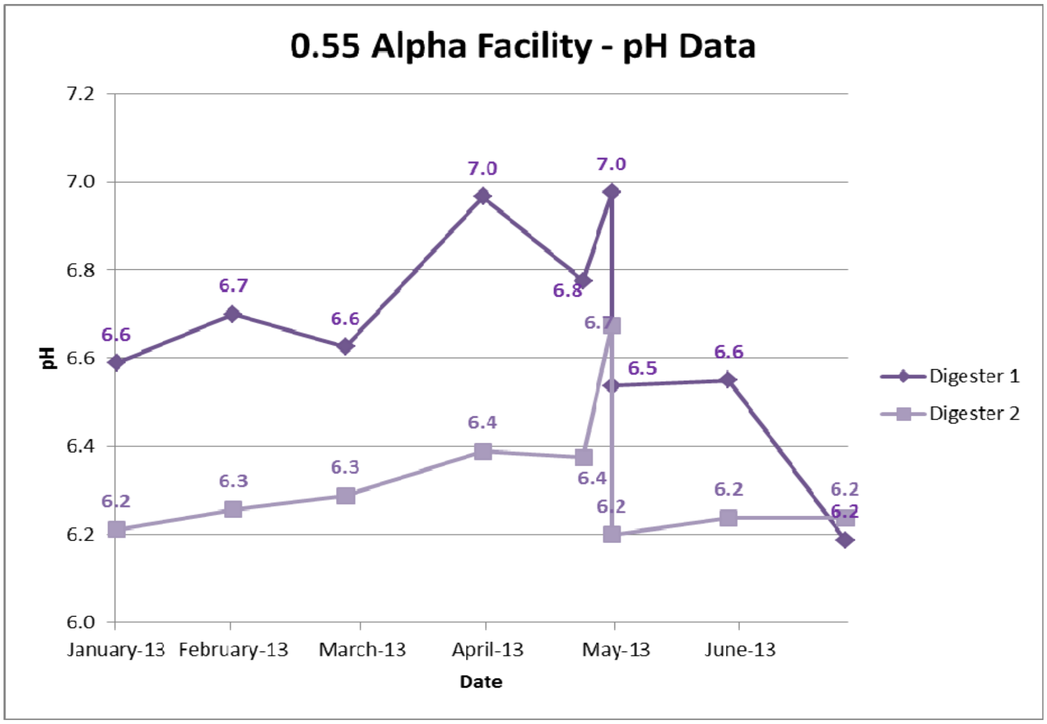
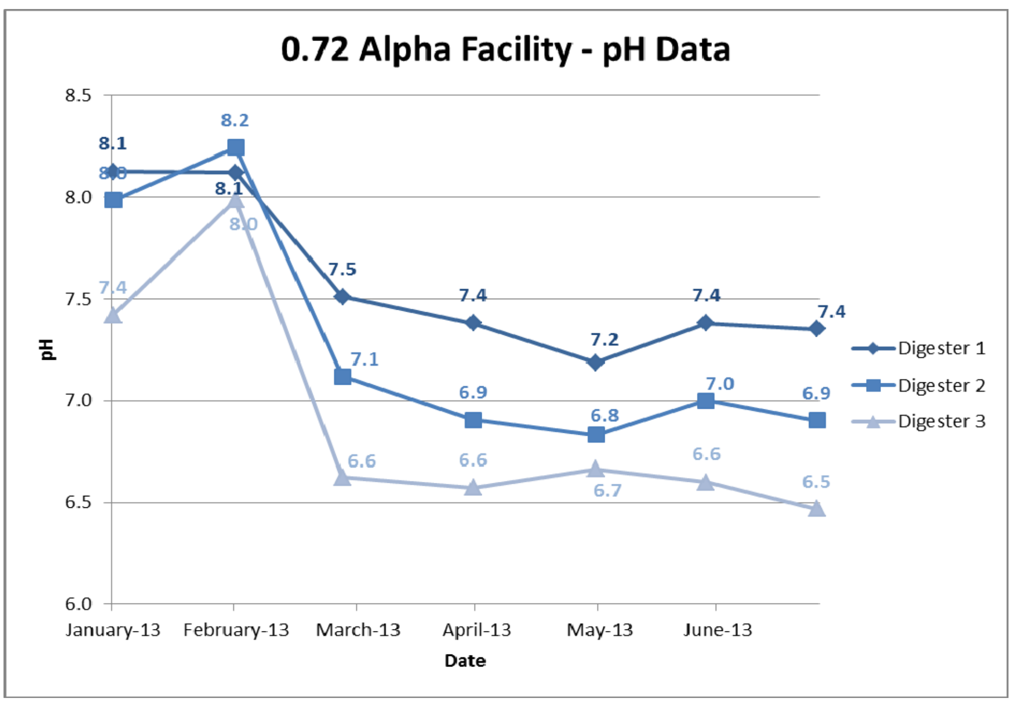


Figure 18: pH Data of 0.72 Alpha Value Facility



Discussion of the Results

The facility that was designed for the lower alpha value of 0.55 yielded better VS reduction results on a more consistent basis. The facility with the aeration system designed for an alpha value of 0.55 had VS reduction that ranges from 35% and 58% with an average of 47%, while the facility with the aeration system designed for an alpha value of 0.72 had a VS reduction that ranges from 32% and 48% with an average of 41%.

Perhaps the most intriguing data here is shown in Figure 15. The 0.55 alpha facility operates solids concentrations from 4.8% to 4.0% while the 0.72 alpha facility operates solids concentrations between 4.0% to 3.0%. The data shows the 0.55 alpha facility operates at total solids concentrations at least 1% more than the 0.72 alpha value facility. The reason for the facility with the 0.55 alpha value design being capable of operating at much higher solids concentrations because it has much better pH and ammonia control which suggests healthy biomass. The pH in first stage digester tank (Digester 1) for the 0.55 alpha facility is maintains a pH typically between 6.6 and 7.0 while the second stage digester (Digester 2) maintains a typical pH from 6.4 to 6.2. The lower pH in the tanks also results in lower ammonia levels in the aerobic digester tanks are between lower than the lab detection limits and 20 mg/L. The results show that this system was able to maintain pH control, ammonia control, and very good volatile solids reduction even when operated at high total solids concentrations between 4.0% and 4.5% year round.

In contrast the 0.72 alpha facility operates at a pH between 8.1 and 7.4 in Digester 1, 8.2 to 6.9 in Digester 2, and 8.0 to 6.5 in Digester 3. The higher pH values exhibited at this facility show ammonia levels from 300 mg/L to 500 mg/L in Digester 1 and 200 mg/L to 300 mg/L in Digester 2. These ammonia levels are shown at pH greater than 7.4. Due to the difficulties maintaining pH and ammonia control, the 0.72 alpha facility had to operate a thinner solids concentration. As shown in both Figure 15 and Figure 18 the 0.72 alpha facility had very high pH when thickening was at the highest concentration and consequently yielded the highest ammonia concentrations typically from 400 mg/L to 500 mg/L. Only when the 0.72 alpha facility operate at lower concentrations between 3.3% and 3.0% did the pH decrease in all the digester tanks and subsequently the ammonia concentrations decreased as well which typically ranged from 20 mg/L to 75 mg/L. The results showed that this system was able not capable of consistently controlling pH and ammonia when operated at total solids concentrations greater than 3.3% and that performance started to drastically improve when the total solids concentrations were between 3.0% and 3.2%.

The data collected from these two facilities support the previous research conducted by Sanitaire, Redmon Engineering, and the independent German studies that proper aeration and mixing is absolutely critical to the success of an aerobic digestion system and as a consequence yields poor performance and will be unable to sustain high solids concentration operations if the aeration and mixing system is not properly designed. Both the facilities examined in this research implemented process optimization techniques such as thickening, temperature control, series and batch operation but the differences in performance between the two systems was substantially different because the aeration systems were designed using different alpha values suggesting the alpha value is an extremely critical parameter when designing the aeration system. The use of the appropriate alpha value when designing an aeration system for an aerobic digestion process is extremely critical to process performance. The data collected also shows that in conjunction with the process optimization techniques, if the appropriate alpha value is utilized in the design of the aeration system outstanding process performance is achievable at solids concentrations greater than 45,000 mg/L which is in contrast to the 20,000 mg/L maximum solids concentrations determined in the studies reviewed for this research.

CONCLUSIONS

Although wastewater contains a very small portion of solids compared to water, sludge management at a wastewater treatment facility is very important as it accounts for a substantial portion of the annual operating expenditures. Although anaerobic digestion systems treat the majority of wastewater solids flow in the United States, aerobic digestion systems are the most commonly utilized solids stabilization process. Since aerobic digestion processes are the most commonly utilized technique and solids stabilization accounts for much of a wastewater treatment plant operating expenditures, it is important to investigate the sludge stabilization sustainability of an aerobic digestion system. A process at a wastewater treatment facility is sustainable if it achieves long term outstanding process performance but also provides considerable economic benefits.

Aerobic digestion systems have been utilized at wastewater treatment facilities for many years therefore this topic has been widely researched, however the literature review conducted in this study has shown a lack of studies on aerobic digestion process optimization techniques with supporting process and economic data. Conceptually an aerobic digestion system is relatively simple however there are many sophisticated design and operational factors that must be considered to make it a truly sustainable process. The primary objectives of this research was to identify the optimization techniques that can be utilized at aerobic digestion facilities, provide process operating and economic data from existing aerobic digestion facilities which supported the use of these techniques, and demonstrate the importance an aeration and mixing system plays in the performance in an aerobic digestion system.

Through this investigation there are five optimization techniques that are utilized in aerobic digestion systems: 1) Tank Configuration, 2) Thickening, 3) Aerobic and Anoxic Operation, 4) Temperature Control, and 5) System Flexibility. The data collected during this research shows that if these techniques are implemented, it can result in tremendous process performance such as enhanced volatile solids reduction, improved solids retention times, pH control, odor control, increased biological capacity, and reduced influent nitrogen and phosphorus influent loading. Improved performance of an aerobic digestion process can also improve other processes in a wastewater treatment plant such as the liquid treatment biological processes by protecting the plant effluent from additional nutrient loadings from biosolids handling systems and dewatering processes by reducing the amount of solids to be processed. In addition to outstanding process performance the data in this research has shown these optimization techniques also provides substantial economic benefits such as reduced disposal costs, energy costs, operation and maintenance costs, capital costs associated with the construction of new process tanks, and chemical costs.

Equally as important to the implementation of optimization techniques the design of the aeration and mixing system affects the performance of an aerobic digestion process. Studies that have been conducted have shown much objection to operating aerobic digestion systems at high solids concentrations (greater than 20,000 mg/L) due to issues with oxygen transfer efficiencies and poor mixing. As shown in this study if the aeration system is not properly designed especially in aerobic digestion processes handling solids concentrations greater than 30,000 mg/L there can be substantial consequences such as lack of volatile solids reduction and problems controlling pH and ammonia. If the aeration system is properly designed such as using appropriate alpha values an aerobic digestion process can achieve sustainable high volatile solids reduction, pH and ammonia control while operating at solids concentrations as high as 45,000 mg/L.

It can be concluded after evaluating the data collected in this study from many aerobic digestion systems, the keys to the sludge sustainability of an aerobic digestion process are process optimization techniques while operating in unison with a properly designed aeration and mixing system.

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APPENDIX

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