EFFECT OF SECONDARY AEROBIC DIGESTION ON PROPERTIES OF ANAEROBIC DIGESTED BIOSOLIDS

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ABSTRACT

In this study, the performance of sequential anaerobic-aerobic digestion was compared to conventional anaerobic digestion for sludge from the Blue Plains Advanced Wastewater Treatment Plant. Volatile solids removal, polymer conditioning demand for dewatering, and biosolids odor characteristics following anaerobic digestion and sequential anaerobic-aerobic digestion were monitored. Aerobic digesters downstream of anaerobic digesters were found to improve overall process performance. For the sequential anaerobic-aerobic digesters, volatile solids removal was more than 60%. Improvement in the biosolids dewatering properties was also found as evidenced by a decrease in the capillary suction time (CST), polymer conditioner dose requirements. Combined soluble protein and polysaccharides present in the anaerobic digester were reduced by 85% after aerobic digestion. Following sequential anaerobic–aerobic digestion, it was observed that sludges that were digested under thermophilic anaerobic conditions produced approximately 30% less odorants than mesophilic digested biosolids and the addition of an aerobic digestion step reduced odorant production by an additional 40%. A test was conducted to simulate winter storage by exposing the biosolids to a single freeze-thaw cycle. Freeze-thaw treatment of digested biosolids showed that even after anaerobic-aerobic digestion, sludges retain a potential for high and rapid odor production. It appears that following freeze-thaw treatment, additional proteins are made bioavailable, resulting in the higher odor generation.

KEYWORDS

Anaerobic digestion, aerobic digestion, dewatering, conditioning, thermophilic digestion, mesophilic digestion, odor
INTRODUCTION

Engineers are constantly searching for ways to increase volatile solids destruction in anaerobically digested biosolids. An increase in volatile solids destruction results in a decrease in dry solids mass, and often an increase in overall dry cake solids content. These changes can thus reducing biosolids management costs. Anaerobically digested biosolids often have poor dewatering properties and they may also generate odors, especially if they are dewatered using high solid centrifuge (Novak, et al., 2006). Poor dewatering and offensive odors are a cause for concern for wastewater treatment utilities due to the additional costs of conditioning biosolids, solids disposal and public relations problems. Therefore, methods to improve dewatering and reduce odors are also desired.

The release of extra-cellular polymer or biopolymer, primarily soluble proteins and polysaccharides, during digestion is considered to be responsible for increasing polymer demand during dewatering (Novak et al., 2003). Research by Novak and Higgins (1997b), and Novak et al. (2003) suggest that different type and quantity of biopolymer are released by anaerobic and aerobic digestion. Subsequent to aerobic digestion, soluble extra-cellular polysaccharides are the predominant biopolymers, while after anaerobic digestion, both soluble polysaccharides and protein accumulates. Thus anaerobically digested biosolids can have a substantially greater polymer demand than aerobically digested biosolids. The post-aerobic treatment of anaerobically digested biosolids could potentially remove some of the accumulated protein and reduce polymer demand.

Park et al. (2006) found that proteins released during anaerobic digestion of various sludge was strongly correlated with VS removal. They also observed that the total VS reduction by either anaerobic-aerobic digestion or aerobic-anaerobic digestion is the same; only the fraction of VS removed during the separate anaerobic or aerobic stage changes. This suggests that there is some portion of VS that can be degraded only by aerobic digestion and some portion degraded only under anaerobic conditions. Subramanian (2005) found improved cake solids and reduced polymer demand for sequential anaerobic-aerobic digested biosolids due to the reduction of bound water and low concentration of proteins and polysaccharide.

The literature suggests that both anaerobic and aerobic digestion processes degrade different portions of sludge and a small fraction of solids can be digested under both digestion processes. Therefore, by utilizing combined anaerobic-aerobic digestion, higher solids destruction and lower odors generation might be possible. The main objective of this study was to determine the effect of sequential anaerobic-aerobic digestion volatile solids removal, biosolids dewatering and odorant production. This study also investigated the influence of simulated winter storage (a single freeze-thaw cycle) on odorant production from digested biosolids.
MATERIALS AND METHODS

Laboratory digester operation

The study was divided into two phases as shown in Table 1, which also summarize the acronyms for the different digesters which are used in the discussion. In the first phase, two complete mixed anaerobic digesters were operated, one mesophilically (35°C) and another thermophilically (55°C). The mesophilic anaerobic digester was operated at 10 days SRT followed by 6 days of aerobic digestion and the thermophilic digester was operated at 20 day SRT with aerobic digester operating at 6 day SRT. In the second phase, both thermophilic and mesophilic anaerobic digesters were operated at 15 days SRT. The two aerobic digesters were operated at 3 days and 9 days SRT for each anaerobic digester. The aerobic digester temperature was maintained at 30 °C.

The anaerobic digesters were fed with 1:1 (by weight) mixture of gravity thickened primary sludge and dissolved air flotation thickened waste activated sludge (DAFT-WAS). The percentage of solids in the feed was maintained 4%. Both primary and secondary sludge were provided by the Blue Plains Advanced Wastewater Treatment Plant operated by the District of Columbia Water and Sewer Authority (DCWASA) on weekly basis by overnight shipment. The feed was stored in a 4 °C room until used. Sludge was fed to the anaerobic digesters once per day and an equivalent volume of digested sludge was removed from the digester. The anaerobic digested solid was fed to the aerobic digesters (Figure 1).

Table 1 - Digester combinations during two phases of study and acronyms of the digesters used during result analysis

<table>
<thead>
<tr>
<th>Study phase</th>
<th>Combination – 1 (SRTs)</th>
<th>Combination – 2 (SRTs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thermophilic anaerobic digestion (55 C) - Stage 1</td>
<td>Sequential Aerobic digestion (30 C) - Stage 2</td>
</tr>
<tr>
<td>1</td>
<td>20 days (Th-20)</td>
<td>6 days (ThAr6)</td>
</tr>
<tr>
<td>2</td>
<td>15 days (Th-15)</td>
<td>9 days (ThAr9)</td>
</tr>
<tr>
<td></td>
<td>3 days (ThAr3)</td>
<td></td>
</tr>
</tbody>
</table>

For anaerobic digestion, plastic conical (egg-shaped) fermenters manufactured by Hobby Beverage Equipment Company were used. Anaerobic digesters were mixed by re-circulating gas from the headspace to the bottom of digester using Cole-Parmer 6-600 RPM variable speed pumps (operated at 40% of their maximum possible speed). The anaerobic digesters were maintained in a 36°C room. The thermophilic digesters were heated by re-circulating hot water at 63 °C through poly-vinyl piping around the thermophilic digester and the digester was wrapped in insulating material to avoid heat loss. Gas produced during the digestion process from anaerobic digesters was collected in air tight Tedlar gas bags and periodic measurement of the
gas volume and gas content was carried out. Due to the high operating temperature, water evaporated from the thermophilic digester and it was captured using a water trap. The average water loss was $50 \pm 2$ ml per day and this water was reintroduced in the digester daily prior to sampling.

**Figure 1** – Typical digestion sequence and configuration of digesters used in the study of anaerobic-aerobic digestion process. Arrows represent the direction of the mass flow.

**Anaerobic-Aerobic sequential Digestion Process**

Aerobic digestion was carried out in stainless steel digesters provided by Blinchmann Engineering, except for digesters operating at short three day SRT. For the three day aerobic digester, nine liter glass containers (Fisher Sci.) were used because of the low operation volume (three liter) of biosolids in the digesters. Mixing in aerobic digesters was achieved using external pumps (Cole Parmer, 6-600 RPM) and compressed air was supplied from a compressor using aeration-stones for oxygen transfer. The dissolved oxygen level in all of the digesters was maintained at $3.0 \pm 0.3$ ppm using flow regulating values.

Sample collection was started after two SRT cycles of the anaerobic digesters during both phases. Total solids, volatile solids and pH were measured in the feed, anaerobic effluent and aerobic effluent on the same day. For cations ions, soluble proteins and polysaccharides measurements, samples were centrifuged at 10,000 g for 20 min at 25 °C, filtered using 1.5 um cellulose filters, followed by filtration through 0.45 um nitrocellulose filters. Filtered samples were stored frozen until the analysis was conducted. Tewatering rate was measured using Capillary Suction Time (CST), and Optimum Polymer Dose (OPD), and for these experiments.
digested solids from anaerobic and aerobic digesters were collected over 3-4 days and kept stored in refrigerator at 4 degree C until experiments were conducted.

**Analytical methods**

Total solids and volatile solids were measured according to Standard Methods for the Examination of Water and Wastewater (APHA 1995). Gas production, percentage gas distribution, pH, DO, digester temperature, chemical oxygen demand (COD), TKN, ammonia, selected dissolved ions and volatile fatty acids (VFA) were conducted and results are discussed elsewhere (Kumar et al., 2006).

For investigating dewatering properties, protein, polysaccharide, cations, CST and polymer dose consumption were measured periodically, while for odor generation, methods developed by Novak et al. (2002) and Muller et al. (2004) were used.

*Cations* – Cation concentrations in the samples were measured using a Dionex D-120 ion chromatograph (Dionex Corp., Sunnyvale – CA). A CS-12 column equipped with conductivity detection with self generating suppression of eluent. 20mM methanesulfonic acid was used for eluent at 1mL/min flow rate.

*Biopolymer Analysis* – Samples from the raw feed, anaerobically digested sludge and from the aerobic digesters were collected twice per week and centrifuged at 10,000 g for 20 min. The supernatant, filtered through 1.5 µm filters (934-AH, Whatman) was used for biopolymer and cation measurements. Samples were filtered and stored at 0°C until used. Filtration using 0.45 µm nitrocellulose filters (Fischer Scientific) was conducted after frozen samples were thawed at room temperature prior to cation measurement. Measurement of soluble proteins was by the modified Lowry et al. (1951) method described by Frølund et al. (1996). Soluble polysaccharides were measured by the Dubois et al. (1956) method utilizing hexose as the standard.

*CST and polymer dose quantification* – A 1% (by weight) solution of solid polyacrylamide polymer, Stockhausen–650, was used for optimum polymer dose determination. For CST measurements, 100 mL of digested sludge conditioned with polymer and sheared using a Waring blender for 30 sec was used. Both a Triton Type 304-M and Triton Type 165 CST apparatus were used with Whatman 17-CHR chromatography paper. The optimum polymer dose was determined as the polymer dose providing the lowest CST.

*Odor sample preparation and measurement* – Odor samples were prepared by simulating the dewatering process of a high-solids centrifuge (Muller, et al., 2004). At the optimum polymer dose, the sludge samples were sheared for 30 sec using a Waring blender. The resultant biosolids were dewatered in two steps, first by centrifugation in a lab centrifuge (operated at 10,000 g for 20 min at 25 C), followed by dewatering using hydraulic piston press by applying 30 psi pressure for 15 min with Whatmann 41 type filter paper as the filtering media. Five
microliter of a 0.127 mM bromoethane sulfonic acid (BESA) solution was added before centrifugation to inhibit methanogenic activity for some of the sludge cakes. The biosolid cakes were incubated in 250 mL I-CHEM glass bottles, and sealed with caps fitted with a Teflon septa, at 25 C. Freeze-thaw samples were stored at 0 C for the desired period of freezing (1 week and 1 month) and thawed for 1 day at 25 C prior to odor testing. After thawing, the samples were dewatered using the lab centrifuge dewatering simulation procedure.

Odor measurements included quantification of H2S (Hydrogen sulfide), CH3S (methanethiol, MT), CH3-S-CH3 (dimethyl sulfide, DMS) and CH3-S-S-CH3 (dimethyl disulfide, DMDS). For reporting purpose, the sum of all organic sulfur gases is reported as organic sulfur. For quantifying the amount of gases, gas samples were collected from the headspace of the sample bottles and measurements were conducted with cyro-trapping and gas-chromatography (Novak et al., 2002).

**RESULTS AND DISCUSSION**

**Phase -1:** For the first phase of study, the anaerobic detention times were selected as part of another anaerobic digestion study running in parallel. A six day aerobic SRT was selected for aerobic digestion of volatile solids as well as to provide sufficient time for nitrifying bacteria to grow.

**Phase -2:** SRTs were selected in this phase to directly compare the performance of the thermophilic, mesophilic digestion and subsequent aerobic digesters. Fifteen days of anaerobic digestion was used since it is a common detention time for anaerobic digesters. For aerobic digestion, three and nine days SRTs were used to investigate the effect of aerobic detention time on volatile solid reduction. From the anaerobic digested effluent. Table 2 summarizes the average values of parameters used for operation monitoring in digesters operated during phase 1 and phase 2.

The large standard deviation in the alkalinity and pH in aerobic digester were due to nitrification in aerobic digesters. The nitrification process consumes alkalinity and the loss of alkalinity results in the pH change.
Table 2 - Digester operation parameters comparison (Average values with standard deviation)

<table>
<thead>
<tr>
<th>Digester details and acronym</th>
<th>Operation Volume (L)</th>
<th>Average pH</th>
<th>Average alkalinity in digester effluent (mg/L as CaCO3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermophilic anaerobic digestion at 15 day SRT (Th-15)</td>
<td>37.5</td>
<td>7.33 ± 0.09</td>
<td>2840 ± 72</td>
</tr>
<tr>
<td>Thermophilic anaerobic digestion at 20 day SRT (Th-20)</td>
<td>20</td>
<td>7.76 ± 0.11</td>
<td>7222 ± 518</td>
</tr>
<tr>
<td>Mesophilic Anaerobic digestion at 10 day SRT (Me-10)</td>
<td>15</td>
<td>7.35 ± 0.06</td>
<td>7191 ± 753</td>
</tr>
<tr>
<td>Mesophilic anaerobic digestion at 15 day SRT (Me-15)</td>
<td>37.5</td>
<td>7.35 ± 0.11</td>
<td>2833 ±155</td>
</tr>
<tr>
<td>Aerobic digester receiving influent from Th-15 with 3 day SRT (ThAer3)</td>
<td>3</td>
<td>7.58 ± 0.35</td>
<td>757 ± 32</td>
</tr>
<tr>
<td>Aerobic digester receiving influent from Th-20 with 6 day SRT (ThAer6)</td>
<td>4.2</td>
<td>7.04 ± 0.64</td>
<td>1340 ± 342</td>
</tr>
<tr>
<td>Aerobic digester receiving influent from Th-15 with 9 day SRT (ThAer9)</td>
<td>6.3</td>
<td>7.30 ± 0.34</td>
<td>576 ± 323</td>
</tr>
<tr>
<td>Aerobic digester receiving influent from Me-15 with 3 day SRT (MeAer3)</td>
<td>3</td>
<td>7.28 ± 0.63</td>
<td>337 ± 67</td>
</tr>
<tr>
<td>Aerobic digester receiving influent from Th-10 with 6 day SRT (MeAer6)</td>
<td>6</td>
<td>7.37 ± 0.62</td>
<td>1449 ± 335</td>
</tr>
<tr>
<td>Aerobic digester receiving influent from Me-15 with 9 day SRT (MeAer9)</td>
<td>6.3</td>
<td>6.85 ± 0.50</td>
<td>277 ± 29</td>
</tr>
</tbody>
</table>

Volatile solids removal during anaerobic and aerobic digestion

Volatile solid removal in anaerobic digestion - Inman et al. (2004) investigated the effect of temperature and SRT on VS reduction for the Blue Plains sludge. Their study showed that Blue Plains sludge has a higher VS reduction during mesophilic digestion than thermophilic digestion. During this study, measurements of total solid and volatile solid were conducted for all digesters and the results from this study also show similar results. Data in Figure 2 provide a comparison of the VS removal during anaerobic digestion at different SRTs and temperatures. Volatile solids removal in the thermophilic digester operating at 20 day SRT was equivalent to the VS removal in the mesophilic digester operating at 15 day SRT, both approximately 52%.

Effect of aerobic digestion SRT on VS reduction - Work by Novak and Higgins (1997 b), and, Novak et al. (2003) suggested that there are two different types of floc organics that are degraded
during aerobic and anaerobic digestion. Park et al. (2006) conducted batch studies for aerobic-anaerobic sequential digestion and anaerobic-aerobic sequential digestion. Their results indicated that some portion of the volatile solids cannot be degraded by either of these digestion processes and some portion can be degraded only by one of the digestion processes. Parravicini et al. (2006) also studied effect of post aerobic stabilization of anaerobic digested sludge and concluded that additional 10% to 22% VSS degradation can be achieved. Aerobic post-stabilization enhance biodegradability of residual organic matter in digested sludge.

**Figure 2 – Comparison of volatile solids reduction in different anaerobic digesters operating at different SRTs. Th-15 VSR data is from digester recovery period.**

In this study, the effect of the aerobic digestion period on total volatile solids removal was investigated. The aerobic digesters were operated at 3, 6 and 9 days. Data shown in Figure 3 compare the VS reduction at the different SRTs and suggest that more than 60% volatile reduction can be achieved with an aerobic SRT as low as three day. Three days of additional aerobic digestion resulted in 20% or more additional VS removal beyond that achieved by anaerobic digestion alone. An increase in aerobic digestion SRT was also found to increases the percentage of VS removal (Figure 4).

*Effect of aerobic digestion on poorly digested sludge* - During the second stage of the investigation, the thermophilic digester failed to perform as expected and this resulted in a low volatile solids reduction. The average VS reduction measured during this period of operation was
16.5% (± 7.75%). Upon subsequent aerobic digestion of poorly digested biosolids from the thermophilic digester, approximately 40% total VSR was achieved at a three day aerobic SRT.

A comparison between the volatile solids removal during the poor performance and good performance of thermophilic anaerobic digestion is shown in Figure 5. The data show that aerobic digestion greatly increases VS removal, especially when the anaerobic stage performs poorly. During the poor anaerobic digester performance, more than 20% additional VS removal was achieved by aerobic digestion at a detention time of 3 days, compared to 14% when the anaerobic digester was performing properly.

Anaerobic-aerobic sequential digestion also has an engineering advantage. It provides an option of optimizing the SRTs of the anaerobic and aerobic phases, thereby minimizing the cost requirements for operation. By optimizing the anaerobic and aerobic phase SRTs, higher volatile solids with less digester volume are required.

**Figure 3 – Effect of post-aerobic digestion SRT on overall sequential anaerobic-aerobic digestion volatile solids removal.**
Figure 4 – Comparison of additional VS removal during aerobic digestion at 3 SRTs. Solid lines represent the linear fitting of data.

![Graph showing additional VS removal during aerobic digestion at 3 SRTs with linear fittings and R² values.]

Table 3 – Comparison of solids and biopolymer in feed, anaerobic and second stage aerobic digesters. Aerobic digestion helped in achieving more VSR and low concentration of biopolymers.

<table>
<thead>
<tr>
<th>Sludge</th>
<th>TS%</th>
<th>VS%</th>
<th>VSR%</th>
<th>Protein (in mg/L)</th>
<th>Polysaccharide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase -1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed</td>
<td>3.9</td>
<td>3.3</td>
<td>1,030</td>
<td>1,030</td>
<td>280</td>
</tr>
<tr>
<td>Th-20</td>
<td>2.1</td>
<td>1.6</td>
<td>51.6</td>
<td>2,370</td>
<td>650</td>
</tr>
<tr>
<td>ThAer6</td>
<td>1.6</td>
<td>1.2</td>
<td>64.4</td>
<td>200</td>
<td>280</td>
</tr>
<tr>
<td>Me-10</td>
<td>1.7</td>
<td>1.7</td>
<td>48.6</td>
<td>1,160</td>
<td>250</td>
</tr>
<tr>
<td>MeAer6</td>
<td>1.3</td>
<td>1.3</td>
<td>60.2</td>
<td>470</td>
<td>250</td>
</tr>
<tr>
<td>Phase -2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed</td>
<td>3.6</td>
<td>2.7</td>
<td>770</td>
<td>160</td>
<td></td>
</tr>
<tr>
<td>Th-15</td>
<td>3.4</td>
<td>2.2</td>
<td>20.2</td>
<td>2,370</td>
<td>300</td>
</tr>
<tr>
<td>ThAer3</td>
<td>2.6</td>
<td>1.6</td>
<td>41.1</td>
<td>1,240</td>
<td>360</td>
</tr>
<tr>
<td>ThAer9</td>
<td>2.5</td>
<td>1.4</td>
<td>48.6</td>
<td>360</td>
<td>160</td>
</tr>
<tr>
<td>Me-15</td>
<td>2.2</td>
<td>1.3</td>
<td>51.5</td>
<td>1,290</td>
<td>160</td>
</tr>
<tr>
<td>MeAer3</td>
<td>1.8</td>
<td>1.1</td>
<td>61.4</td>
<td>250</td>
<td>280</td>
</tr>
<tr>
<td>MeAer9</td>
<td>1.6</td>
<td>0.9</td>
<td>67.5</td>
<td>350</td>
<td>100</td>
</tr>
</tbody>
</table>
Relationship between biopolymer and dewatering

Soluble Protein in anaerobic & aerobic sludges - The data presented in Table 3 shows that during anaerobic digestion, biopolymer is released from the sludge matrix and this was consistent with the investigations of Novak et al. (2003) and Novak et al. (2004). During this study, it was observed that polysaccharide and protein concentrations approximately doubled during thermophilic anaerobic digestion. During mesophilic digestion, the protein concentration in solution was found to increase about 25 % in phase-1 and 12 % in phase-2, but the polysaccharide concentration declined.

Proteins in sequentially anaerobic-aerobic digested sludge were found to decrease (Figure 6). It was observed that after three day aerobic digestion, more than 50% of the extracellular soluble protein was removed. The average protein removal after 6 day aerobic digestion of thermophilic digested sludge was 88% and was 65% for the mesophilic anaerobic-aerobic system.

Soluble Polysaccharide accumulation and removal - Figure 7 shows the average polysaccharide concentration in the anaerobic digested sludge and in aerobic digesters for different digestion periods. The thermophilic digested biosolids contained higher soluble polysaccharide concentrations than the mesophilic biosolids. In addition, the percentage removal of polysaccharides was greater in the thermophilic anaerobic–aerobic sequence (more than 60% after six days aerobic digestion). For the mesophilic anaerobic system, the post-aerobic digestion impacts on soluble polysaccharide concentration is less clear.

Thermophilic anaerobic-aerobic digestion shows better overall biopolymer removal during digestion than the mesophilic anaerobic-aerobic sequence (Figure 8). Total biopolymer removal was approximately 80% after 6 days of post-aerobic SRT in the thermophilic sequence, while in the mesophilic anaerobic-aerobic sequence the maximum removal was 70% after 9 days of post-aerobic SRT.

CST and polymer dose requirement - The optimum polymer dose and CST (at optimum polymer dose) were measured after the anaerobic digesters attained steady state. Figure 9 and Figure 10 show the optimum polymer dose and corresponding minimum CST. Overall, the thermophilic anaerobic biosolids had a lower CST and lower polymer dose requirement than mesophilic anaerobic digested sludge. The CST and OPD for the thermophilic digested sludge was different from the results observed by Higgins et al., 2006. The possible reasons for the difference were the sludge characteristics and pH of the digested biosolids.
Figure 5 – Comparison of performance of thermophilic digestion on VSR basis and role of aerobic digestion in attaining cut-off VSR limits.

![Graph showing comparison of performance]

Figure 6 – Protein concentration of influent and effluent for aerobic digesters. Day 0 protein concentrations are average concentration measured during 2 phases in respective anaerobic digesters.

![Graph showing protein concentration]

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Figure 7 – Polysaccharide concentration of influent and effluent for aerobic digesters. Day 0 polysaccharide concentrations are average concentration measured during 2 phases in respective anaerobic digesters.

Comparison of CSTs for anaerobic digested biosolids and anaerobic-aerobic sequentially digested biosolids (Figure 11 and Figure 12) suggests that a substantial reduction in the CST and optimum polymer dose can be attained after sequential aerobic digestion at SRTs as low as three days. Data in Figure 13 shows that a lower polymer dosage was required at optimum CST by thermophilic anaerobic-aerobic digested sludge (for aerobic digestion period of less than six days) than for mesophilic anaerobic-aerobic biosolids. From Figure 12, it was also interpreted that polymer requirement and CST decrease with an increase in aerobic digestion SRT for mesophilic biosolids.

CST and polymer dose are considered to be related to the protein and polysaccharide present as biocolloids in the digested sludge suspension. These biocolloids carry a negative charge and for efficient dewatering, charge neutralization is required. The results in this study show an overall decrease in biopolymer during the aerobic stage of sequential digestion and as a result, the CST of the sludge improves and polymer dose consumption is reduced.
Figure 8 – Comparison of effect of aerobic digestion SRTs and influent type on the total biopolymer conc. removal in the aerobic digesters.

Figure 9 – Comparison of Capillary suction time (CST) for the anaerobic digested sludges.
Figure 10 – Comparison of polymer dose requirement for the anaerobic digested sludges. NOTE: Data for the Th-15 digester were collected during the poor performance period.

Figure 11 – Effect of aerobic stage SRT and influent sludge in aerobic digesters on the CST. Day-0 data are the representative average value of CSTs measured for anaerobic digested sludges from different phases.
Figure 12 – Optimum polymer dose requirement after the aerobic digestion and effect of influent sludge on the polymer requirements. Day-0 data are the representative average value of CSTs measured for anaerobic digested sludges from different phases.

![Graph showing polymer dose requirement vs. aerobic digestion SRT](image)

**Odor generation**

*Effect of temperature and methanogenic activity on odor production* - Adams et al. (2003) conducted a study on odor generation from anaerobically digested sludges which were collected from various treatment plants. The study found that total volatile sulfur gas generation from the dewatered biosolids depended upon the sludge characteristics and biosolid treatment train. One of the important conclusions from this study was that even properly operating anaerobic digesters produced odors. It was of interest to determine if sequential aerobic digestion could reduce odors because sequential anaerobic-aerobic digestion was found to enhance solids destruction during the digestion process, and a correlation between the digestion period and odor potential had been observed (Verma et al., 2005).

Headspace gas concentrations from the anaerobically digested sludge cakes were measured using the headspace method of Novak et al. (2002) and the peak volatile organic sulfur concentration data from dewatered solids from the digesters are presented in Table 4. The data indicate that more volatile organic sulfur is produced from the biosolids which were digested under mesophilic anaerobic conditions than for the thermophilic digested sludges. In addition, the mesophilically digested sludge produced organic sulfur gases much more rapidly, peaking approximately after 5 to 7 days, compared to the thermophilic sludge which had a peak organic sulfur concentration at day 33. The thermophilic biosolids produce a low peak organic sulfur concentration, but the organic sulfur persists for a longer duration (about 40 days). The results are consistent with the WERF-II study (Adams et al., 2003) which also reported higher organic...
sulfur over a shorter duration from the mesophilic digested biosolids in comparison to the low organic sulfur for longer duration from the thermophilic digested biosolids. The main reason for difference in the organic sulfur generation profiles was believed due to the differences in the genre of sulfur reducing bacteria present in thermophilic and mesophilic sludge. It was thought that in thermophilic digested sludge, bacteria with the ability to convert the sulfur-containing amino acids, cysteine and methonine to mercaptans and dimethylsulfide are not as common as in the mesophilic digested solids. Therefore, the organic sulfur peaks usually appear later than that in the mesophilically digested sludges.

The role of methanogens in odor production was described by Chen et al. (2005) who found that methanogens convert methanethiol and other organic sulfur compounds to sulfide. When methanogenic activity in the sludge samples was inhibited, high organic sulfur concentrations were measured (Table 5, Figure 15, Figure 16 and Figure 17). In these tests, methanogenic activity was inhibited by addition of 5 mL BESA to the sludge prior to incubation (Bouwer et al., 1983).

Role of Anaerobic and aerobic phase SRT - Investigations concerning the effect of SRT on odorant generation suggest that an increase in the anaerobic digestion period reduces the organic sulfur generation from the resulting biosolids. Figure 13 and Figure 16 show the effect of anaerobic SRT on organic sulfur with BESA addition. The peak organic sulfur concentration in the BESA amended sludges is considered to be the odorant potential of that sludge and when biosolids were amended with BESA, an increase in anaerobic digestion period resulted in a decrease in the organic sulfur concentrations. In Figure 14, the effect of the aerobic digester SRT is shown. It can be seen that for the thermophilic sludges, the aerobic SRT has little effect on organic sulfur gas potential while for the mesophilic anaerobic-aerobic sludges, the odorant potential decreases as the aerobic SRT increases. This suggests that thermophilic anaerobic digestion produces a sludge with a lower odorant potential and the added aerobic treatment does little for additional odor reduction. In contrast, the aerobic treatment of mesophilic digested solids has a positive effect on odorant potential. Figures 13 and 14 show about a 20% reduction in organic sulfur from mesophilic digested biosolids after 3 day of aerobic digestion and after 9 days of aerobic digestion, more than 55% odorant production potential can be reduced.

Effect of simulated winter storage (Freeze-thaw) – Freeze thaw treatment of the biosolids samples was carried out to understand the effect of natural weather cycles on the odor production from the biosolids. The investigation suggests (Figure 17, Figure 18 and Figure 19) that high concentration of organic sulfur odorants are produced upon thawing biosolids that were frozen for a period of one week. Anaerobic thawed samples show an increase in organic sulfur of approximately 75% and the peak occurs in one to two days. In the sequential anaerobic-aerobic digested solids, (Figure 17 and Table 5) it can be seen that the additional aerobic digestion at low SRTs does little to reduce organic sulfur generation for the freeze thawed sludges. This was inconsistent with the unfrozen sludges where aerobic digestion of mesophilically digested anaerobic sludge substantially reduces organic sulfur. It appears that during the freeze period, additional protein is released from the sludge and biodegraded by microbes once the sludge was...
thawed, leading to a rapid production of sulfur gas. Organic sulfur concentrations from the solids digested anaerobically followed by three day aerobic digestion produced as high as 300% more odors than unfrozen anaerobic-aerobic samples. Only the longer aerobic digestion (SRT of 9 days) periods were found to produce less organic sulfur (Figure 19). This suggests that increase in SRT of second stage aerobic digester may help in decreasing the odor generation from biosolids which may get exposed to freezing conditions but only if the aerobic SRT is 9 days or longer. Other post-digestion methods to solve this particular odorant problem are warranted.

Figure 13 - Odorant potential (odorant from BESA amended biosolids) changes as a function on anaerobic digestion SRT.
Figure 14 – Changes in Odorant potential in sequential anaerobic-aerobic digested biosolids as a function of aerobic digestion SRT. More dramatic change was observed for mesophilic sludge than thermophilic.

![Graph showing changes in odorant potential](image)

R² = 0.6032
R² = 0.9971

Figure 15 – Comparison between the typical odor generation profiles of different anaerobic digested biosolids and effect of simulated winter storage (freeze-thaw) on the odorant generation from biosolids. (NOTE: FzTh – Freeze Thaw)

![Graph comparing odor generation profiles](image)
Figure 16 – Comparison of organic sulfur concentration in Mesophilic digested biosolids and mesophilic biosolids spiked with BESA for inhibiting methanogenic activity in sample. High digestion period reduces the odors from the biosolids.

Table 4 - Peak organic sulfur concentration in biosolids samples prepared from different sludges and treatments.

<table>
<thead>
<tr>
<th>Sludge</th>
<th>Un-amended</th>
<th>BESA One week Freeze Thaw</th>
<th>One month Freeze Thaw</th>
<th>Digester Headspace odor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(in mg/ cubic meter)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Th-15</td>
<td>352</td>
<td>616</td>
<td>406</td>
<td>NA</td>
</tr>
<tr>
<td>Th-20</td>
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<td>203</td>
<td>NA</td>
<td>15</td>
</tr>
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<tr>
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<td>1,105</td>
<td>993</td>
<td>14</td>
</tr>
<tr>
<td>ThAer3</td>
<td>261</td>
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<tr>
<td>MeAer9</td>
<td>153</td>
<td>71</td>
<td>53</td>
<td>NA</td>
</tr>
</tbody>
</table>
Figure 17 – Comparison of typical odor production curve after only anaerobic digestion, sequential anaerobic-aerobic digestion and freeze thaw treatment of both anaerobic and anaerobic-aerobic digested samples.

Figure 18 – Effect of freeze-thaw period and digestion time on the odor production from biosolids samples.
Figure 19 – Effect on odor generation tendency of biosolids due to aerobic stage digestion period and influent sludge. The biosolids were treated under freeze-thaw cycle of 1 week.

CONCLUSIONS

This study concludes that –

1. Sequential anaerobic-aerobic digestion assists in achieving more than 60% volatile solids removal, with minimum 3 days of aerobic digestion.
2. Aerobic digestion also safeguards the overall digestion process, if the anaerobic digester is performing poorly.
3. More than 50% solution protein plus polysaccharide removal can be achieved by subsequent aerobic digestion of anaerobically digested sludge.
4. Organic sulfur generation was found to decrease with an increase in anaerobic digestion period as well as aerobic digestion SRT. A five day increase in anaerobic digestion SRT reduced approximately 20% odorant potential of anaerobic biosolids. Three days of additional post-aerobic SRT resulted in a further 25% decrease in odorant potential of mesophilic digestion solids.
5. Thermophilic biosolids generate 50% lesser organic sulfur in comparison to mesophilic biosolids, but the organic sulfur production period lasts longer than that for mesophilic biosolids.
6. Simulate winter freeze-thaw cycling makes organic sulfur generation more rapid and of higher concentration once the frozen samples are thawed.
7. A longer post-aerobic digestion period reduced the odorant production from the freeze-thaw biosolids. Solids post-aerobically digested for 9 day were found to produce 50% less organic sulfur after freeze-thaw than those which were digested for 3 days.

REFERENCES


