FACT SHEET

High Performance Anaerobic Digestion

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Introduction

At the heart of biosolids processing improvements is high performance anaerobic digestion (HPAD). Digestion performance improvements result in more treatment capacity per unit volume to convert wastewater residuals to nutrient-rich, low-odor biosolids, more efficient conversion of organics to methane-rich biogas, and to improve overall biosolids quality. Although there are many conventional high rate mesophilic digestion systems that perform at a high level, there are system modifications to increase performance, which include raising to a thermophilic temperature, decoupling the hydraulic retention time (HRT) and solids retention time (SRT), increasing the solids concentration and pre-treatment processes enhancing hydrolysis, and cyclic metabolic environments.

Hydrolysis

Hydrolysis is the rate limiting step during anaerobic digestion of complex materials. Hydrolysis describes a group of reactions whereby complex materials are degraded into simpler ones by extracellular reactions catalyzed by enzymes. The simpler compounds formed are small enough to be transferred across a bacterial cell membrane where they can be further processed. Hydrolysis of waste activated sludge (WAS) has often been described as the rate limiting step with respect to the anaerobic degradation of wastewater sludge. To make it more amenable to digestion, the sludge can be broken down using processes that enhance this hydrolysis step in digestion. These fall into the following categories:

- Thermal
- Biological
- Chemical
- Physical

The benefits of pre-processing waste vary. The intent is to enhance the rate and extent of volatile solids (VS) destruction, increase biogas production, and improve sludge rheology. It must be noted, however, that while the rate of biogas production increases compared to an absence of hydrolysis, the yield of biogas produced – based on quantity of material degraded – remains constant as that is fixed by stoichiometry. Some of the hydrolysis processes convey other benefits such as improved dewaterability or ability to meet Class A requirements for pathogen destruction as defined under the U.S. Environmental Protection Agency (EPA) 40 CFR Part 503 regulation.

Thermal Hydrolysis

The thermal hydrolysis process (THP) involves the application of heat at above sterilization temperature (>250 °F or 120°C) coupled with pressure. This is a mature technology with over 20 years of commercial operation, primarily in Europe, with multiple suppliers and configurations. The THP arrangement varies by manufacturer and can be either a batch (Figure 1) or a continuous flow process. It is typically installed prior to digestion, either on all of the sludge or only on the WAS, as the benefits of the pre-treatment process are much more pronounced on the WAS (Figure 2).

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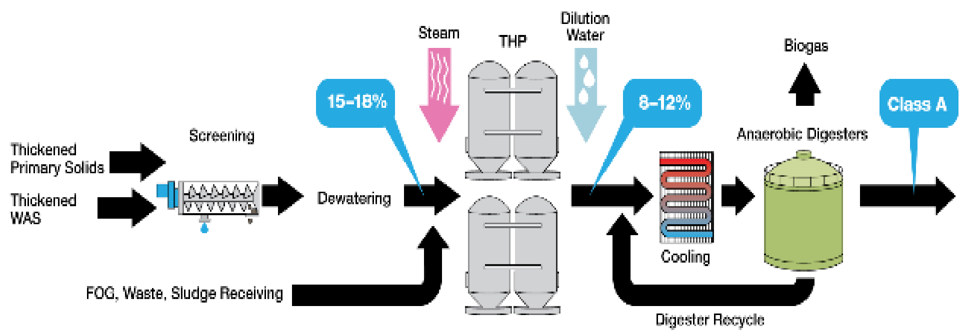

Figure 1: Thermal Hydrolysis – Batch Configuration

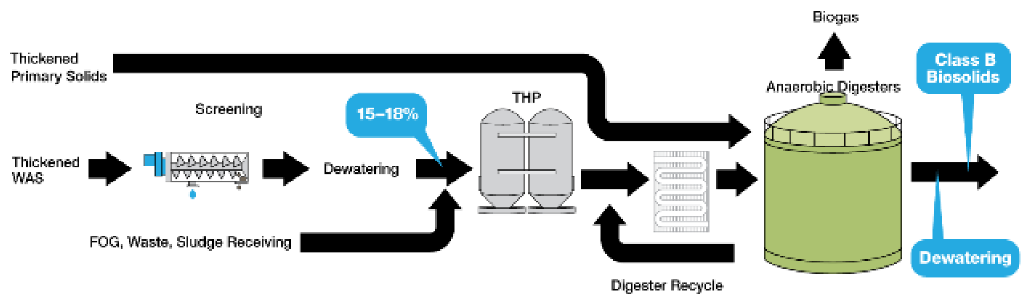

Figure 2: WAS-Only Thermal Hydrolysis

For one manufacturer's batch process, sludge is dewatered to between 15 and 18 percent dry solids prior to the application of heat to reduce energy requirements. The dewatered material is then pre-heated using recovered heat and brought to reaction temperature using steam, which reduces its dry solids content by approximately 2 percentage points. Once at temperature, the sludge remains in a batch for 20 to 30 minutes before it is rapidly decompressed. The sludge is then cooled and diluted to reduce potential for ammonia inhibition in the anaerobic digesters. The fundamental benefit of THP is a change in sludge rheology (the flow characteristics of non-Newtonian fluids). This allows for feeding a high solids concentration (approximately 10 percent dry solids) at higher loading rates (in the range of 0.35 to 0.50 lb VS/day/ft^3) while still being able to mix the digester. Higher loading rates are particularly important when building new facilities as the digestion volume required can be less than half. Conversely, the throughput of existing facilities can be more than doubled.

If THP is configured to treat WAS only, primary solids will be combined with hydrolyzed WAS prior to the anaerobic digesters. This configuration is beneficial if sterile cake is not required. Benefits of WAS-only THP include smaller THP equipment, reduced steam (energy) demand, and substantial reduction or elimination in the cooling step prior to digestion. However, WAS-only THP generates less biogas (by 10-20 percent) and requires larger digester tank volume, due to the minimum 15-day SRT requirement to comply with Class B Biosolids requirements.

Other benefits include sludge sterilization (if both primary solids and WAS are treated), and destruction of extracellular polymers which influence dewaterability. As with all processes which improve anaerobic digestion, the ammonia release is higher, and this is observed in filtrate or centrate from dewatering. Although concentrations are typically over twice normal digestion, the additional load is approximately 20 to 30 percent higher when VS destruction is higher. The biology of a THP anaerobic digester (THP-AD) is different than a conventional digester and is conditioned to both the high loading rates and high ammonia concentrations. For this reason, the startup and operation of THP-AD requires careful planning to ramp up to full loading. Once the THP-AD is stably operating, the high loading and high ammonia conditions should be maintained in order to avoid an upset. However, the higher concentrations of ammonia make the filtrate or centrate well suited to high rate treatment. The major disadvantage of THP is the provision of the energy required for heating (steam), although the majority of the heat demand can be met via usage of biogas for use in steam boilers or waste heat from a cogeneration plant. Also, with higher temperatures in the pre-treatment process, cooling is often necessary, which requires ancillary systems.

More recently, alternative configurations have appeared which places the THP downstream of first stage anaerobic digestion (Figure 3). In one of these configurations, an intermediate THP is installed downstream of a first stage of digestion and prior to a second stage digestion. In this way, the plant is hydrolyzing only the less biodegradable material, which makes the THP system smaller. Additionally, the heat demand is met with no need for auxiliary fuel. However, this configuration requires more digestion capacity than the conventional application of thermal hydrolysis prior to single stage anaerobic digestion.

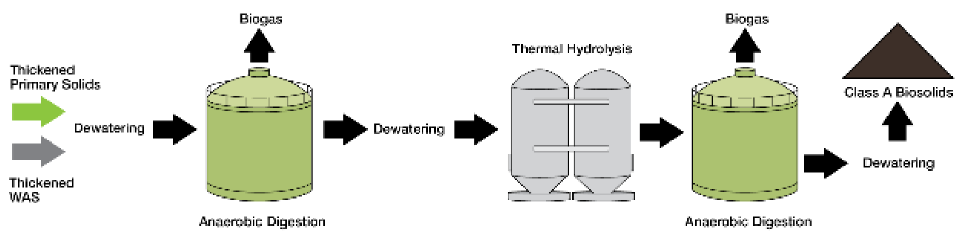

Figure 3: Intermediate Thermal Hydrolysis

Finally, THP is being considered downstream of anaerobic digestion in order to maximize dewatering benefits. Here, digested sludge is dewatered (as mentioned earlier) for thermal hydrolysis (Figure 4). The filtrate or centrate containing ammonia from the digester is then returned to the head of the plant for treatment. The thickened material is then dewatered in a second stage. The dewatering stage provides a granular odor-free material and a high strength biodegradable centrate which can be recycled to the anaerobic digester or processed in a separate high rate digestion plant. By doing this, both dewatering and biogas production are increased compared to other configurations of THP. It has not yet been determined if this configuration achieves Class A biosolids.

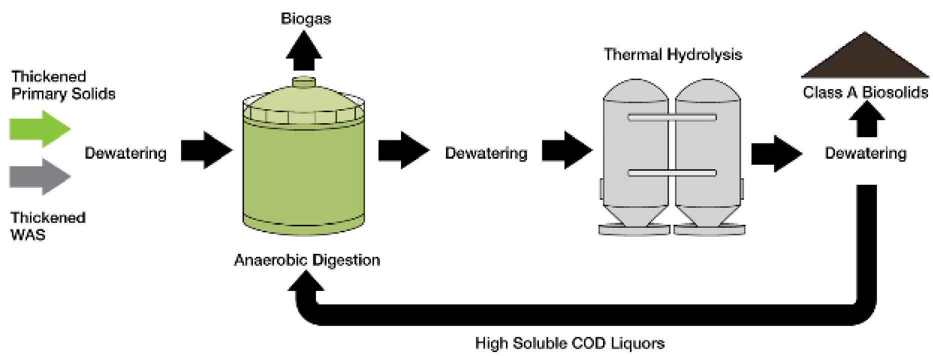

Figure 4: Thermal hydrolysis downstream of anaerobic digestion

Biological Hydrolysis

With biological hydrolysis, sludge is pre-conditioned in a fermenter vessel or vessels, which, due to different environmental conditions, favor the production of volatile fatty acids (VFAs) which are the precursors of substrate for methanogens ultimately producing the biogas.

The most well-known biological hydrolysis system is the acid/gas (A/G) phased digestion process that consists of a highly loaded "acid-phase" digester followed by more lightly loaded "gas-phase" digester (Figure 5). The concept was originally proposed in the 1970s and comprises of providing separate, ideal environments for the acid forming and gas forming microorganisms. The first stage is designed to provide pretreatment (primarily hydrolysis and acidification) and the second stage is designed for maximizing gas production. A typical design has a first stage with an SRT of about 1.5 days, which effectively selects for acid formers because of faster reaction kinetics than methane formers. The build-up of acids depresses pH to approximately 5.5. Typically, the second stage has an SRT of approximately 10 days. The major advantage of the A/G process is improved VS destruction in a smaller volume than a typical mesophilic digestion process. The process is also reported to help mitigate digester foaming.

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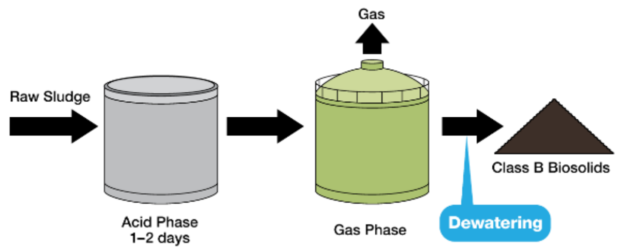

Figure 5: Acid/Gas Phased Digestion

Another version of biological hydrolysis is known as Enzymic Hydrolysis (Figure 6). As with A/G digestion, sludge is held prior to digestion for a short SRT for acids to form. Unlike A/G digestion systems, the preliminary stage is based on typically using 6 smaller reactors in series rather than a single vessel. For Enzymic Hydrolysis, the reactors are kept at 107 °F for 2 days. To meet the requirements of Class A, an enhanced Enzymic Hydrolysis process was developed, which has the same 6 tanks except that the last two are operated at 145 °F. As the process operates at lower pressures and temperatures than THP, improvements in both biogas production and other factors are generally less, however, the energy demand is also concurrently less. Additional infrastructure for the multiple tanks is also required.

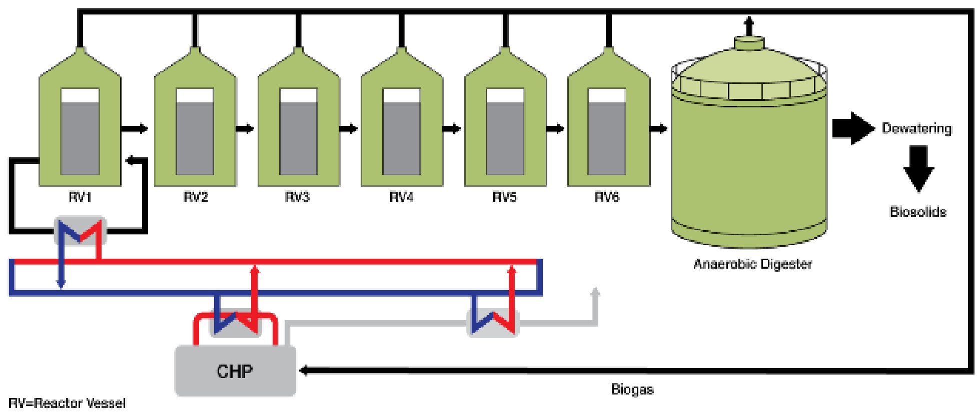

Figure 6: Enzymic Hydrolysis

Chemical

Hydrolysis can also be achieved by adding abrasive materials, and the use of both acids and alkalis has been well documented.

Thermo-Chemical Hydrolysis

Thermo-chemical hydrolysis uses caustic soda and elevated temperatures to hydrolyze cell membranes of WAS at a high pH and temperature (Figure 7). Organic acids released in the process are converted more quickly during the anaerobic digestion process, which can increase biogas production by up to 30 percent compared to standard rate anaerobic digestion at relatively low SRTs. The hydrolyzed sludge allows for dryer cake solids and lower polymer consumption. The viscosity of the hydrolyzed sludge is drastically lowered (by up to 80 percent), creating more efficient pumping and digester mixing. By using the heat from the hydrolysis process to heat the anaerobic digesters, operational costs of the system can be further minimized. At this time, there are a very limited number of operating systems, but the efficacy of full-scale systems appears to be promising.

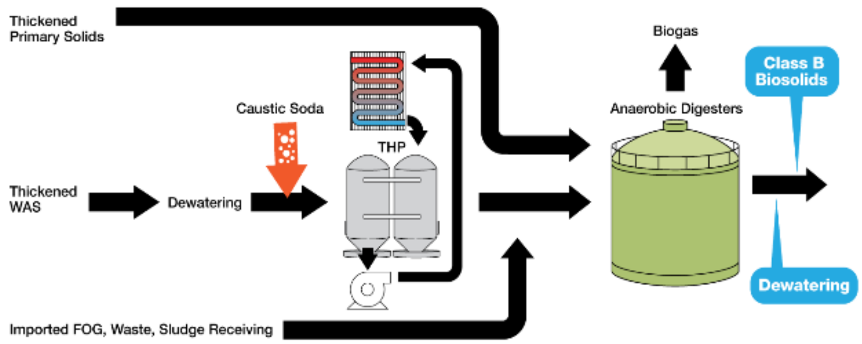

Figure 7: Thermo-Chemical Hydrolysis

Physical

There are numerous processes which hydrolyze sludge through mechanical processes, including pressure release, electric pulse, microwave, and ultrasound waves. In this way, microbial cells are broken up and release their contents which can be converted ultimately into biogas resulting in improved performance. Of these processes, ultrasound is the most common. Here, an electric pulse is converted to ultrasound by a transducer which transfers the energy to a metal (typically titanium alloy) where it is converted to cavitation energy.

The important factors to consider when looking at ultrasonic instruments are their power output, the technology used to convert the electrical signal into ultrasound (typically magnetostrictive or piezoelectric, the latter being more efficient), and the geometry of the probe (as this limits the power which can be applied). In addition, there is debate among providers as to how much sludge should be processed. Some suppliers sonicate all sludge, while others only hydrolyze the WAS.

Chemical Augmentation

Enzyme Addition

In addition to conditioning sludge prior to digestion, it is possible to improve biodegradability by adding specific chemicals, such as nutrients and enzymes. The concept of enzyme addition is based on the addition of biological catalysts which enhance certain reactions. Because enzymes are highly specific in the reactions they catalyze, an abundant supply of enzymes must be present in cells to carry out all the different chemical transformations required. Most enzymes help break down large molecules into smaller ones and release energy from their substrates. To date, scientists have identified over 10,000 different enzymes. Attempts to develop specific bacteria and enzyme solutions to enhance the digestion of municipal wastewater sludge and other waste streams with the aim of improving performance and increasing biogas yields are in progress. However, while a number of enzymes for wastewater treatment from various industries have been developed, the development of enzymes for anaerobic digestion has been much slower. This technology may prove to be of interest in the coming years with respect to improving performance and increasing biogas production.

Nutrient Addition

The anaerobic digestion process, like any other biological system, may be enhanced by nutrient addition. In anaerobic systems, trace nutrient deficiencies can lead to increased VFA concentrations that depress pH, increase chemical oxygen demand (COD) and solids accumulation, and limit the overall treatment efficiency. Anaerobic digestion requires adequate trace metal bioavailability and presence of sulfide. Trace metal deficiency can cause elevated VFAs in an anaerobic digesters. Nutrients that have proven to stimulate biogas production include iron, copper, selenium, cobalt, manganese, tungsten, nickel, molybdenum, boron and zinc.

Mesophilic

High Rate Digestion

Modern mesophilic digestion is often referred to as high rate digestion, differentiating it from previous practices which had minimal heating or mixing provided. Mesophilic anaerobic digestion is a common process, representing the majority of anaerobic digesters that are currently in operation. While other HPAD processes serve to improve performance, many of the basic principles remain the same. There are a number of best practices to improve, optimize and make this process more robust and safe, even if more substantial upgrades are not presently feasible for a facility.

- Digester configurations typically involve at least two evenly-heated and well-mixed digesters, though in some cases only one tank is used. Operation in series may improve performance, although caution is required to avoid overloading the first stage digester. A combined SRT of 15 days is required to produce Class B Biosolids.
- For improved performance, digesters must be fed continuously or nearly so, avoiding any spikes in liquid or solids feed or concentration. Care must be taken to load multiple parallel digesters equally, especially when SRT is close to 15 days or the VS loading is high.
- Adding food waste, grease and other high-strength wastes can significantly improve digester performance and gas production but feedstocks must be carefully selected, controlled, and received to avoid contamination, toxicity, and digester upsets. The dewaterability and quality of the final biosolids product may be impacted by these practices and should be considered.
- Digested solids storage or a “secondary digester” with varying liquid level provides flexibility and facilitates intermittent dewatering operations. Cover selection must be appropriate to allow flexibility while preventing under- or over-pressure events. Digesters that operate at a constant liquid level may be covered with fixed steel or concrete covers. If the liquid level is to vary frequently, floating or gasholder (steel or dual-membrane) covers are often used.
- Mixing should be provided for all digesters. Some recent tests have shown that methane production in digesters is unaffected or even improved with little to no mixing. However, the need for proper mixing goes beyond gas production and is done to ensure consistent temperature and sludge properties, prevent/reduce foam and scum and decrease grit accumulation. Preventing grit accumulation will ensure the SRT is maximized over long periods of time.
- Solids withdrawal points should be located near the top and bottom of tanks to prevent accumulation of low-density solids and floating debris and reduce grit accumulation. Surface withdrawal capability is recommended to allow removal of scum, foam, or less dense material.
- Proper operation for prevention, and mitigation of rapid volume expansion and foaming events is essential. Sufficient freeboard, emergency overflows and other protections should be included to prevent damage. Emergency-relief manhole covers should be used on fixed digester covers.

High Solids Digestion

Thickening the feed (up to approximately 8 percent dry solids) can significantly reduce digester heat demand and required tank volume (or increase the SRT). Mixing becomes the limiting factor for high solids digestion in the absence of pre-treatment to reduce viscosity (such as hydrolysis). There are mixing systems available reported to function well at these high solids concentrations.

Typical anaerobic digestion has been a “once through” process where the HRT is equal to the SRT. Recuperative thickening increases the SRT in the same digester volume by returning some of the digested sludge back into the digestion process to increase the solids retention time and the mass of solids digested. There are also proprietary processes for an integrated system of thickening and digesting a higher solids concentration in the digester. The process may be applicable when an increase in SRT without an increase in digester volume can help achieve regulatory or interim operating needs.

Thermophilic

Thermophilic anaerobic digestion is similar to mesophilic digestion, except the process occurs at higher temperatures, about 122° to 135° F (50° to 57° C). The higher temperatures help to increase the pathogen reduction. Thermophilic microorganisms have more rapid reaction rates than mesophilic microorganisms.

Advantages of thermophilic digestion include higher loading rates, increased solids destruction, pathogen reduction, and improved sludge dewaterability versus conventional mesophilic anaerobic digestion. Disadvantages of thermophilic digestion include larger energy requirements, and higher odor generation. The larger energy requirements can be offset by providing thicker feed sludge or using recovered heat from the digested sludge to heat the raw sludge. Providing consistent temperature is key because thermophilic microbial populations are more sensitive to temperature changes than mesophilic populations. Thermophilic digestion configurations include single-stage, staged, and temperature phased anaerobic digestion (TPAD).

Single stage thermophilic digestion has a similar configuration to conventional mesophilic digestion and operates with a minimum SRT of 15 days. Staged Thermophilic includes a large digester (SRT= 8 to 12 days) followed by one or more smaller digesters (SRT= 1 to 2 days, each) in series (Figure 8). Flow-through configurations do not meet Class A biosolids criteria. However, batch processes can be configured to meet the time-temperature (Alternative 1) requirements.

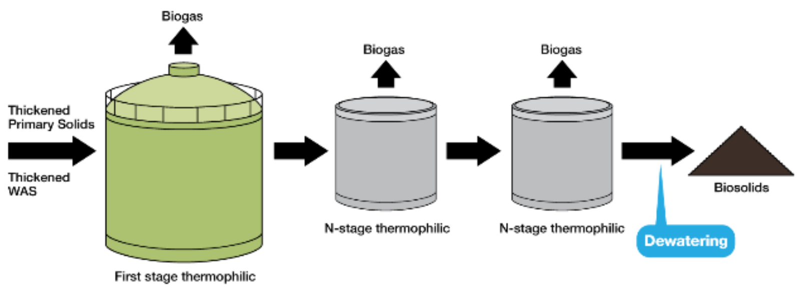

Figure 8: Staged Thermophilic Digestion

TPAD consists of two digesters in series and can be configured as either thermophilic-mesophilic or mesophilic-thermophilic. The most common configuration includes a thermophilic phase (SRT= 4.5-6 days) followed by a mesophilic phase (SRT= 10-12 days) (Figure 9). This configuration can meet Class A biosolids requirements through Alternative 1 by implementing batch operation of the thermophilic digesters to prevent short-circuiting of untreated sludge. Providing a mesophilic digester downstream of the thermophilic phase mitigates odors.

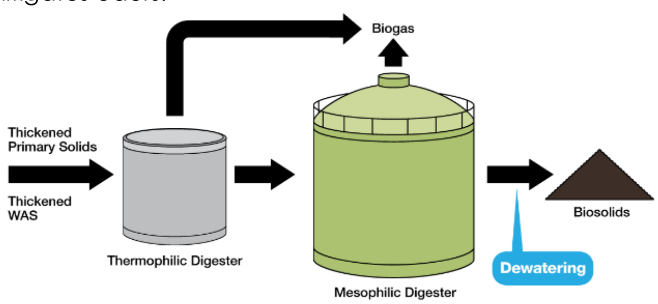

Figure 9: Temperature Phased Anaerobic Digestion

Combined Aerobic/Anaerobic Digestion

Aerobic digestion could be used as a pretreatment to anaerobic digestion or as a post-treatment after anaerobic digestion. Combining aerobic and anaerobic digestion could result in significant benefits. Those benefits may outweigh the cost of the aeration energy input and the reduction in sludge energy value from oxidation.

Aerobic Followed by Anaerobic Digestion

Aerobic digestion pretreatment involves adding air or oxygen to solids at thermophilic temperatures of approximately 131° to 149° F (55° to 65° C). The main benefits are potential increased VS reduction and higher levels of pathogen destruction. If thermophilic aerobic treatment is operated to comply with time and temperature requirements of 40 CFR Part 503, the final biosolids product is considered Class A. Typically this would require that the aerobic pretreatment is operated in a batch mode.

The aerobic pretreatment could be either heated externally or operated as auto-thermal process. For the auto-thermal operation, the aerobic reactions in the digester release sufficient heat to raise the reactor temperature to the thermophilic range, eliminating the need to preheat sludge prior to anaerobic digestion. The SRT of the aerobic pretreatment is in the range of 1 to 2 days dictated by the time and temperature requirement. In case of auto-thermal digestion, the VS content in raw sludge also affects the target SRT. More volatile matter in the raw sludge will cause more rapid heating, reducing the SRT requirement.

Overall performance of the solids treatment is known to have slightly better VS reduction than conventional mesophilic anaerobic digestion. In addition, the same level of treatment could be achieved with shorter anaerobic digester SRT (9 to 12 days), compared to a standalone mesophilic anaerobic digestion with typical retention times of 15 to 20 days. The most known successful operation of this process is Tacoma, Washington, where this process has been in operation for more than 10 years.

Anaerobic Followed by Post-Aerobic Digestion

Aerobic digestion as a post-anaerobic digestion treatment addresses different goals, compared to the aerobic pre-treatment. This process has been reported to increase VS reduction, reduce struvite impacts downstream of digestion, improve dewaterability of sludge, decreases polymer requirements, and decrease nuisance odors in the final biosolids product. In addition, aerobic post-treatment reduces the impact of nutrient loading to the plant from dewatering sidestream. In some cases, aerobic sludge post-treatment can serve as an alternative to side stream nutrient removal process. This is especially beneficial for utilities facing stringent ammonia or nitrogen discharge limits.

Post-treatment digesters are designed for an SRT of 5 to 15 days. The temperature in the digester is closely monitored and controlled to remain under 104° F (40° C) to provide stable nitrification. The aerobic digester can also be designed for varying liquid level operation to serve as a holding tank prior to dewatering. The aeration system can be designed to achieve complete nitrification but it may require alkalinity addition to prevent acidification of the reactor. The process can also be designed to achieve nitrification and denitrification through intermittent aeration or low dissolved oxygen operation.

Spokane County Regional Water Reclamation Facility, City of Boulder's 75th Street Wastewater Treatment Facility, and Denver Metro Water Reclamation District's Northern Treatment Plant have been operating this process for several years.

Conclusion

As illustrated in this document, the anaerobic digestion process continues to be improved through process modifications and supplemental treatment mechanisms. Many wastewater treatment facilities have prioritized the recovery of resources as the charter of the organization to meet environmental stewardship objectives. Anaerobic digestion continues to be a robust process to convert wastewater residuals to energy and safely reuse the biosolids product to supplant fertilizer and enhance soil. The importance of anaerobic digestion is evidenced by the continued improvements, modifications, and upgrades to the digestion process.

Reviewers

David Parry; Chris Wilson; Irina Lukicheva; Lauren Fillmore

Further Reading

1. Solids Process Design and Management, WEF Press 2012
2. 40 CFR Part 503: Standards For The Use or Disposal of Sewage Sludge, EPA
3. Design of Municipal Resource Recovery Facilities, WEF MOP 8, 6th Edition, 2018
4. Operation of Municipal Resource Recovery Facilities, WEF MOP 11, 7th Edition, 2017
5. Wastewater Engineering, Metcalf & Eddy, 5th Edition, 2014

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