1 Biogas Production Through Anaerobic Digestion

Biogas can be produced from a broad range of feedstocks that are suitable for anaerobic digestion, unlike the production of other popular renewable fuels that are feedstock constrained. For instance, current ethanol technology requires feedstocks with high fermentable carbohydrate levels (e.g. corn, sugarcane, sugar beets, potatoes), while biodiesel production requires feedstocks with high oil content (e.g. waste vegetable oils or virgin vegetable oil from oil seed crops). Both technologies require extensive pre-processes of feedstocks and only yield fuel from a portion of the native biomass material. In contrast, biogas can be made from most biomass and waste materials regardless of the composition and over a large range of moisture contents, with limited feedstock preparation. Feedstocks for biogas production may be solid, slurries, and both concentrated and dilute liquids. In fact, biogas can even be made from the left-over organic material from both ethanol and biodiesel production.

Most of the existing installations are processing residual sludge from wastewater treatment plants. Other facilities are processing wastes from chicken processing, juice processing, brewing, and dairy production. However, the range of potential waste feedstocks is much broader including; municipal wastewater, residual sludge, food waste, food processing wastewater, dairy manure, poultry manure, aquaculture wastewater, seafood processing wastewater, yard wastes, and municipal solid wastes. Food processing wastewaters may come from citrus processing, dairy processing, vegetable canning, potato processing, breweries, and sugar production.

There are many potential energy crops, which may be suitable for biogas production including: sugarcane, sorghum, napier grass, as well as, woody crops (tree crops). The best crops should have low fertility requirements, and low energy costs for planting and harvesting. Further, ethanol production from an energy crop will produce large volumes of stillage wastewater, which can be converted to biogas. Also, the production of biodiesel from oil crops produces a glycerol wastewater that also may be converted to biogas.

The process of anaerobic digestion consists of three steps:

1. The first step is the decomposition (hydrolysis) of the organic material. This step breaks down the organic material to usable-sized molecules such as sugar.
2. The second step is the conversion of decomposed matter to organic acids.
3. Finally, the acids are converted to methane gas.

Process temperature affects the rate of digestion and should be maintained in the mesophillic range (95°F to 105°F) with an optimum of 100°F. It is possible to operate in the thermophillic range (135 °F to 145 °F), but the digestion process is subject to upset if not closely monitored.

The following sections further detail the three steps of anaerobic digestion.

1.1 Hydrolysis/liquefaction

In the first stage of hydrolysis, or liquefaction, fermentative bacteria convert the insoluble complex organic matter, such as cellulose, into soluble molecules such as sugars, amino acids and fatty acids. The complex polymeric matter is hydrolyzed to monomer, e.g., cellulose to sugars or alcohols and proteins to peptides or amino acids, by hydrolytic enzymes, (lipases, proteases, cellulases, amylases, etc.) secreted by microbes. The hydrolytic activity is of significant importance in high organic waste and may become rate limiting. Some industrial operations overcome this limitation by the use of chemical reagents to enhance hydrolysis. The application of chemicals to enhance the first step has been found to result in a shorter digestion time and provide a higher methane yield (RISE-AT, 1998).

Hydrolysis/Liquefaction reactions:

- Lipids → Fatty Acids
- Polysaccharides → Monosaccharides
- Protein → Amino Acids
- Nucleic Acids → Purines & Pyrimidines

1.2 Acetogenesis

In the second stage, acetogenic bacteria, also known as acid formers, convert the products of the first phase to simple organic acids, carbon dioxide and hydrogen. The principal acids produced are acetic acid (CH_3COOH), propionic acid (CH_3CH_2COOH), butyric acid ($CH_3CH_2CH_2COOH$), and ethanol (C_2H_5OH). The products formed during acetogenesis are due to a number of different microbes, e.g., syntrophobacter wolinii, a propionate decomposer and sytrophomonos wolfei, a butyrate decomposer. Other acid formers are clostridium spp., peptococcus anerobus,lactobacillus, and actinomyces (www.biogasworks.com-Microbes in AD). An acetogenesis reaction is shown below:

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

1.3 Methanogenesis

The third and final stage is where methane is produced by bacteria called methane formers (also known as methanogens) in two ways: either by means of cleavage of acetic acid molecules to generate carbon dioxide and methane, or by reduction of carbon dioxide with hydrogen. Methane production is higher from reduction of carbon dioxide but limited hydrogen concentration in digesters results in that the acetate reaction is the primary producer of methane (Omstead et al, 1980). The methanogenic bacteria include methanobacterium, methanobacillus, methanococcus and methanosarcina. Methanogens can also be divided into two groups: acetate and H_2/CO_2 consumers. Methanosarcina spp. and methanothrix spp. (also, methanosaeta) are considered to be important in AD both as acetate and H_2/CO_2 consumers. The methanogenesis reactions can be expressed as follows:

$$\underset{\text{(acetic acid)}}{CH3COOH} \rightarrow \underset{\text{(methane)}}{CH4} + \underset{\text{(carbon dioxide)}}{CO2}$$

$$\underset{\text{(ethanol)}}{2C_2H_5OH} + CO_2 \rightarrow CH_4 + 2CH_3COOH$$

$$CO_2 + \underset{\text{(hydrogen)}}{4H_2} \rightarrow CH_4 + \underset{\text{(water)}}{2H_2O}$$

1.4 Biogas from Sludge, Manure and Source Separated Organic Food Waste (SSOW)

The anaerobic digestion of sludge is perhaps the oldest anaerobic digestion technology. Despite the many advances made in reactor designs for wastewater treatment, few can be applied in treatment of sludge, manure and SSOW, as the high suspended solids content of this waste impedes biomass immobilization. However, a better understanding of the anaerobic digestion process has resulted in increases in organic loading rate (OLR) and process performance for sludge and manure treatment. In addition, the tendency of sludge and manure to cause odors and to host pathogens benefits the application of anaerobic digestion for treatment of these wastes for both odor and pathogen reduction, as well as energy production.

Anaerobic digestion occurs over a range of operating temperatures. Two operational temperature levels are typical for anaerobic digestion. Unheated digesters fluctuate with air temperature, and heated digesters (mesophilic digesters) operate near "body temperature" at 95–105°F. Generally, the higher the temperature, the faster the digestion and the greater rate of biogas production. Digesters can also operate at thermophilic condition (131°F).

The most common type of digesters are unmixed systems called plug-flow digesters (Figure 1-1 and 1-2). Plug-flow digesters account for 53% of the digesters in the United States (EPA AgStar). In a plug-flow digester, the materials flow as a plug in a horizontal direction, advancing toward the outlet whenever new materials are added. The reactors may be in-ground, tubular tanks or covered, concrete-lined trenches. This type of reactor can handle materials containing 11–14% total solids and can be insulated and heated to speed up biogas production. Most animal manure, when produced by the animal, is in this moisture range. Plug-flow digesters are best used when little to no bedding or flushing water is added. The average length of time that a material remains in the reactor is the hydraulic retention time (HRT) and ranges from 15–30 days

Figure 1-2

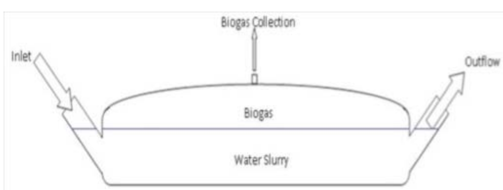

Figure 1-1

Complete-mix digesters (Figures 1-3 and 1-4), which account for 28% of the digesters in the United States (EPA AgStar), are mixed systems where the materials within the reactors are mixed either mechanically with effluent recirculation or with compressed biogas. This type of digester is usually made of a round tank that is insulated and heated. Complete-mix digesters process materials containing 3–10% total solids. Hydraulic retention times range from 10–20 days (Penn State College of Agricultural Sciences). These types of digesters are the most common for source separated organic waste.

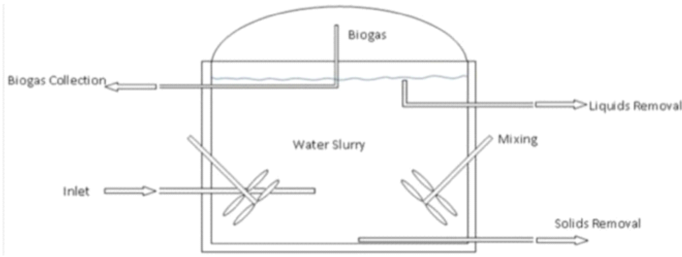

Figure 1-3

Figure 1-4

Covered lagoons are large anaerobic lagoons covered with a flexible or floating gas-tight cover designed to capture biogas (Figure 1-5). Most of these lagoons are not heated and can only handle materials containing 0.5–2% total solids. Retention time for covered lagoons ranges from 30–45 days or longer depending on the size of the lagoon and the outside temperature. Covered lagoons are typically used with flush-style manure management systems. About 15% of the digesters in the United States are covered lagoons.

Figure 1-5

1.5 Characteristics of Sludge, Manure and SSOW

In contrast to wastewater, the principle component contributing to the organic strength of sludge and manure is organic suspended solids (OSS). The most important parameters for characterizing these slurries are total solids content (TS) and volatile solids content (VS). While chemical oxygen demand (COD) could also give a measure of the organic strength of slurries, sampling difficulties and limits of the COD procedure make COD measurements of slurries impractical. There is an upper limit for TS content above which the material is no longer a slurry and mixing and pumping becomes problematic. This upper limit for TS is dependent on the rheological properties of the OSS making up the slurry (i.e., the branch of physics that deals with the deformation and flow of matter, especially the non-Newtonian flow of liquids and the plastic flow of solids). For most manure, sludge and SSOW streams, this occurs at a TS of 10-15%. Waste with a higher TS content may be a candidate for high solids treatment or it will require dilution (preferably with effluent) if it is to be treated as a slurry.

Water is a principal component of manure, sludge and SSOW and facilitates the ability to transport the OSS as a fluid. However, not only does the water content dilute the potential bioenergy content of the slurry, it also may impact anaerobic digester design and operation, by increasing the digester volume due to hydraulic retention time (HRT) limitations. Also, for mesophilic and thermophilic processes, the water content increases the consumption of heating energy. For slurries at 1% TS or less with an ambient temperature of 68ºF, digestion at mesophilic temperatures may consume the majority of biogas produced. Thus, in treatment of slurries with less than about 2% TS, pretreatment methods for concentrating the solids should be considered. If treatment of the separated liquids is desired, then anaerobic wastewater treatment processes should be considered for the liquid fraction.

When considering biogas production from a slurry, the VS content of the material is as important as the TS content, since it represents the fraction of the solid material that may be transformed into biogas. Most manure and sludge from municipal wastes have a VS content of 70-90% of the TS content. The fixed solids (FS, also termed the ash content) is comprised of inorganic material (grit, minerals and salts), which dilute energy content and can impact the treatment process. For some sludge from industrial sources, high FS may come from the use of process chemicals (e.g. lime precipitation).

Although the VS content is an indicator of potential methane production, the specific methane yield on a VS basis is not a constant, in contrast to the specific methane yield on a COD basis which is precisely 5.61 Ft^3/lb (0.35 m^3/kg) COD destroyed. This is due to the composition of the VS of the waste which includes both readily degradable organic compounds including lipids, proteins, and carbohydrates, as well as more refractory organics which may include lignocellulosic materials, complex lipopolysacharides, structural proteins (keratin) and other refractory organics. For pure carbohydrates the specific methane yield on VS basis is 6.09 Ft^3/lb (0.38 m^3/kg) VS destroyed, for proteins the yield varies depending on amino acid profile and averages 9.61 Ft^3/lb (0.6 m^3/kg) VS destroyed and for pure lipids (vegetable oil) the specific methane yield is 16.01 Ft^3/lb (1.0 m^3/kg) VS destroyed. This difference can be attributed to the high H:C ratio of lipids compared to carbohydrates. The complex nature of the composition of an organic waste means that the methane yield is best determined from anaerobic treatability assays on a suitable sample. Biochemical Methane Potential, or BMP, tests are the common anaerobic treatability tests used. The use of BMPs provides a relatively inexpensive and repeatable method to make relative comparisons of the anaerobic digestibility and potential biogas production between various substrates. Biochemical Methane Potentials can be used to determine the amount of organic carbon in a given material that can be anaerobically converted to methane and to evaluate potential biogas production efficiency of the anaerobic process on a given material. The information provided by BMPs is valuable when evaluating potential anaerobic substrates and for optimizing the design and operation of an anaerobic digester.

Finally, other components of sludge and manure can affect anaerobic treatment. For some manures (poultry and swine), the high protein levels in the manure contain significant amounts of nitrogen and sulfur which, upon mineralization to ammonia and sulfide, can limit the OLR due to their inhibitory effects. The sulfide also impacts biogas utilization and clean-up requirements. In municipal and industrial sludge, there is a potential for high concentrations of heavy metals, which can cause inhibition or competitive micronutrient deficiencies when anaerobic treatment is applied to these wastes. Also, inhibitory chemicals present in the sludge from industrial sources or in municipal sludge receiving industrial wastewaters can cause operational problems in anaerobic sludge digestion.

1.6 Digestate

Digestate is the material that is left over following the anaerobic digestion process. Digestate can be made into products like:

- Bedding for livestock;
- Flower pots;
- Soil amendments; and
- Fertilizers.

When properly processed, dewatered digestate can be used as livestock bedding or to produce products like flower pots.

Digestate can be directly land applied and incorporated into soils to improve soil characteristics and facilitate plant growth. Digestate can also be further processed into products that are bagged and sold in stores. Some emerging technologies can be employed post-digestion to recover the nitrogen and phosphorus in digestate and create concentrated nutrient products, such as struvite (magnesium-ammonium-phosphate) and ammonium sulfate fertilizers (see "Digestate: What Can I do with it?" – White Paper).

2 FACTORS THAT CAUSE ANAEROBIC DIGESTION (AD) PROBLEMS

Now that we understand the basics of anaerobic digestion to make biogas, this section provides some helpful insight into common problems encountered in operating facilities. Generally speaking, anaerobic digesters are easy to operate, often requiring very little operational intervention. But vey little does not mean none.

Operators can and do encounter AD problems from time to time. These problems can inhibit the biological process of the plant and have consequences on its production capacity and profitability (what?? Noooo!).

The following is an AD plant troubleshooting guide, including a list of factors the operator should pay attention to and some examples of problems that can occur and how to solve them.

When the AD plant is not working as designed or to prevent problems with the process, the operator should investigate or verify these factors. Note, there are other potential root causes, but based on experience, these factors below are the root cause of 99% of AD problems (not presented in order of importance).

2.1 AMMONIA (NH3)

Ammonia is a compound of nitrogen and hydrogen that is produced during the digestion process. Factors such as temperature, inputs composition, pH and bacteria acclimation influence the effect of ammonia on this process.

Operator Focus:

The operator should make sure the ammonia concentration stays under 2000 ppm or between 50 to 200 mg/L to avoid biogas plant problems. Concentration levels that are between 1500 and 3000 mg/L can inhibit the process and cause digestion failure. However, mesophilic digesters can support more than 3000 ppm if it is well acclimated to ammonia. Ammonia levels that are higher than 3000 mg/L can be toxic for the process.

When the operator notices the concentration of ammonia is climbing, he should reduce the organic loading rate.

2.2 ALKALINITY (ALK)

The capacity of water to neutralize acids in the biogas plant is called alkalinity (ALK). We measure ALK in milligrams of equivalent calcium carbonate per liter. It is used to measure carbonates, bicarbonates, hydroxides and, sometimes, borates, silicates and phosphates.

Operator Focus:

The operator should make sure the ALK stays between 1,500 and 5,000 mg/L. The buffering capacity of the digester content influences the stability of the digestion process. It should also be noted that small pH variations can affect methanogens. Acid producers can function with a wide range of pH.

Testing ALK is an easy and affordable test, which can be done on-site with rapid results with equipment that should cost less than $250 on a first investment basis. There are several manufacturers of ALK test kits for industrial applications, like Hach.

2.3 RATIO BETWEEN VOLATILE ACIDS AND ALKALINITY

The operator can calculate the ratio between volatile acids and alkalinity to control the digestion process better. Similar to testing for ALK, volatile acids tests can be done easily and affordable using a test kit such as the Hach DRB200.

Operator Focus:

The operator can use the following formula to calculate this ratio:

$$\frac{VA}{ALK}\ ratio = \frac{VA\ (\frac{mg}{l})}{ALK\ (\frac{mg}{l})}$$

If the ratio is:

Below 0.35: Digester operations are proper

Between 0.1 and 0.35: The digester is well-operated

+ 0.35: The digester experiences issues like increased organic loading, hydraulic overloading or others.

2.4 OXYGEN

The anaerobic digestion process produces some oxygen even though it occurs with the absence of it.

Operator Focus:

The anaerobic digestion process requires below 0.1 ppm of oxygen in the environment, which is very little. Regular monitoring (installed instrumentation) of oxygen levels in the AD, including PLC trending reviews is recommended.

2.5 VOLATILE FATTY ACIDS (VFA)

Volatile fatty acids, or organic acids, shows the health of the digester. VFAs are also used as a food for the methane formers. They are measured in milligrams of equivalent acetic acid and are soluble in water. The production of VFA varies according to the quantity of solids supplied to the digester.

Operator Focus:

The concentration of volatile fatty acids should be below 2,000 ppm. A higher concentration can off-balance the biology of the system and be toxic. The digester can overload, and the operator can experience other biogas plant problems when the concentration is over 300 ml/L.

The monitoring of VFAs is often done with on-line analyzers such as the Hach Z series. The EZ Series Online Analyzers offer multiple options to monitor Volatile Fatty Acids in water. There several different devices based on the anticipated range of VFAs in the stream. Also, most applications require the use of a sampling/filtration system for sample preconditioning. There are a handful of manufacturers of on-line VFA analyzers. This information can be outputted to the plant PLC and trended for monitoring.

2.6 ORGANIC LOADING

The operator can measure organic loading based on mass or weight of volatile solids per unit of digester volume per day, or kg/m^3 x d and lb/100 ft^3 x d.

Operator Focus:

The organic loading of anaerobic digestion systems can range between 1.6 and 6.4 kg/m^3 x d, or 100 and 400 lb/100 ft^3 x d. In any case, however, the operator should supply the digesters at a consistent and constant rate.

2.7 GAS PRODUCTION

Anaerobic digestion produces methane gas, which can be converted into fuel, heat or electricity. Anaerobic digesters can produce between 6 and 18 ft^3/lb, or 0.8 and 1.1 m^3/kg, of volatile solids destroyed, depending on the feedstock. The normal composition of digester gas is approximatively 65% methane and 35% carbon dioxide. The heat value of the gas stays between 510 BTU/ft^3 and 650 BTU/ft^3 (19 and 24MJ/m^3).

Operator Focus:

The simplest, and oldest test involves having the operator verify the color of the flame at the waste gas burner. If the flame is blue, the digester produces quality methane. If the flame is yellow, the level of carbon dioxide the digester contains is increasing.

Too much carbon dioxide in the digester could hint at a digestion process problem. It could also cause other downstream unit operations issues, depending on what the biogas is used for (i.e., power generation, renewable natural gas production.)

In most modern applications, the installation of an on-line methane analyzer is often used. This data can be outputted to the PLC and trends can be observed.

2.8 SALT LEVEL

The anaerobic digestion process also produces salt (salinity), but its accumulation can affect the production and cause other kinds of biogas plant problems.

Operator Focus:

The operator should make sure the salinity concentration stays between 3,500 to 5,500 ppm. There are several manufacturers that produce affordable devices that measure specific conductivity. Specific conductivity (or just conductivity, which already is a specific measure) measures a substance's ability to conduct electricity. This measure of conductivity in water is used to determine salinity. While the conversion from the former to the latter uses a long equation of several terms, you can use an online calculator to make the conversion with just three variables.

- Convert your conductivity measurement's unit from siemens per meter (S/m) to milli-siemens per centimeter (mS/cm). In other words, multiply by 10. (if your meter indicates mS/cm skip this step)
- Raise the conductivity (in mS/cm) to the power 1.0878.
- Multiply the result by 0.4665. This gives you salinity in grams (of salt) per liter of solution.

2.9 HEAVY METAL

Heavy metal like copper can enter the digester because of industrial users. Traces of heavy metal is beneficial for the anaerobic digestion process. However, a higher concentration can be toxic to the process.

Operator Focus:

The soluble concentration of heavy metal should stay below 0.5 mg/L.

2.10 TEMPERATURE VARIATION

The temperature in the biogas plant should be constant.

For example:

The temperature in a mesophilic digestion system is normally between 85°F and 100°F (30°C and 38°C)

The temperature in a thermophilic digestion system is normally between 122°F and 140°F (50°C and 60°C).

Operator Focus:

The operator should also pay attention to any temperature variation that occurs during the anaerobic digestion process. It should not vary more than ~ 1ºF (0.6°C) for a mesophilic digestion system.

The temperature is these systems should ideally stay between 95°F to 98°F (35°C and 37°C). The retention time should range between 10 and 30 days.

The operator should look for any changes in a thermophilic digestion system, as temperature variation is especially hard on these microorganisms. The retention time for these systems should range between 5 and 12 days.

The operator of the plant can check the heating system and the PLC program if he notices any temperature variation in the mesophilic and thermophilic digestion systems.

2.11 FOAMING

The production of foam during the anaerobic digestion process can decrease its performance and cause safety issues, damaged equipment and/or structures.

Operator Focus:

The operator should pay attention to the mixing, temperatures variations in the digester and/or incorrect or inconsistent supplying if there is foam. It should also be noted that the transfer of filaments from the liquid process stream to the digesters can create foam.

2.12 MIXING

The operator should mix the contents of anaerobic digesters to make sure the temperature stays constant and that the supplied solids are well dispersed. The mixing should be good and thorough for optimal operation.

Operator Focus:

If a mixer or pump doesn’t work, the operator should look in the user manual of the equipment for troubleshooting. He can also ask for technical assistance to repair any parts.

2.13 STRUVITE CREATION

Struvite is a magnesium ammonium phosphate compound ($MgNH_4PO_4$). It forms scale deposits in anaerobic digesters and in the downstream dewatering system. When this happens, struvite can cause maintenance problems, such as clogging pipes, valves, heat exchangers and more.

Operator Focus:

The operator should pay attention to any deposits of struvite in the digesters because they are difficult to remove. There are ways to remove these deposits, such as acid washing, but it is time-consuming and can be a safety issue. Other facilities use ferric chloride or ferrous chloride in digesters to prevent struvite deposits.

3 WHAT ARE THE PROBLEMS THAT CAN OCCUR IN AD PLANTS?

Here are examples of problems that can occur in a biogas plant, their causes, and solutions to solve them.

Problems	Most likely causes	Recommended action
Gas yield has dropped	• Drop in quality of substrates • Drop of temperature • Compounds inhibition • Non-homogenous substrates • Drop of methanogenic bacteria	• Assure substrates mixing and quality • Check heating system • Check level of potential inhibitor compounds • Add digestate from another digester if the methanogenic bacteria as drop
Methane concentration dropped	• Drop in quality of substrates • Drop of temperature • Compounds inhibition	• Assure substrates mixing and quality • Check heating system • Check level of potential inhibitor compounds
Foaming problem	• A new substrates with high protein content has been added • Air is introduced in the digestion • Temperature is changing	• Reduce or stop feeding • Analyze substrates • Reduce air introduction
pH dropped	• Feeding rate is too high or variable • Operating temperature have changed • Agitation is not working	• Reduce substrates until system returns to normal • Use only design feedstock until system returns to normal
FOS/TAC ratio has increased	• VFA rate is too high • Change in feedstock • Lack of buffer • Compounds inhibition	• Reduce OLR • Use only design feedstock

4 Summary

Anaerobic digestion of organic matter to produce biogas is an age-old technology. It has been reported that the first AD was built in Bombay, India in 1859 and became popular in England by the end of the 19th century. It is a fairly simple and robust process that can operate on a wide range of feedstocks with minimal operator attention. AD can be deployed at varying capital costs to fit most budgets. Covered lagoons are the least costly to install, but require a lot of land, while mixed reactors have the highest first cost, but require the least amount of land. Supplemental heat is also often desired to expedite the bioconversion process and increase yields. Of course, there are other design considerations as well and a professional engineer / consultant can help you navigate the decision-making process and provide you with a successful project within your budget constraints.

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