Carcass Disposal: A Comprehensive Review

National Agricultural Biosecurity Center Consortium
USDA APHIS Cooperative Agreement Project
Carcass Disposal Working Group

August 2004

Chapter

7

Anaerobic Digestion

Authors:

Larry E. Erickson	Chemical Engineering, Kansas State University
Eric Fayet	Chemical Engineering, Kansas State University
Bala Krishna Kakumanu	Chemical Engineering, Kansas State University
Lawrence C. Davis	Biochemistry, Kansas State University

Table of Contents

Abbreviations

ANAMMOX	anaerobic ammonium oxidation
BSE	bovine spongiform encephalopathy
C/N ratio	carbon to nitrogen ratio
CWD	chronic wasting disease
END	exotic Newcastle disease
FMD	foot and mouth disease
GVRD	Greater Vancouver Regional District
HRT	hydraulic retention time
MPN	most probable number
OLR	organic loading rate
UASB	Upflow Anaerobic Sludge Blanket
UK	United Kingdom
US	United States
VS	volatile solids

Section 1 – Key Content

The management of dead animals has always been and continues to be a concern in animal production operations, slaughter plants, and other facilities that involve animals. In addition, episodes of exotic Newcastle disease (END) in the United States (US), bovine spongiform encephalopathy (BSE, or mad cow disease) in Europe and elsewhere, chronic wasting disease (CWD) in deer and elk in North America, and foot and mouth disease (FMD) in the United Kingdom (UK) have raised questions about how to provide proper, biosecure disposal of diseased animals. Carcass disposal is of concern in other situations—from major disease outbreaks among wildlife to road-kill and injured-animal events.

Proper disposal systems are especially important due to the potential for disease transfer to humans and other animals, and due to the risk of soil, air, and groundwater pollution. Anaerobic digestion represents one method for the disposal of carcasses. It can eliminate carcasses and, at the same time, produce energy; but in some cases it is necessary to conduct size-reduction and sterilization of carcasses on-site before applying anaerobic digestion technology. These preliminary measures prevent the risk of spreading the pathogen during transportation and reduce the number of digesters needed. Sometimes, if the quantity of carcasses is large, it may be necessary to distribute carcasses between several digesters and to transport them to different locations.

This chapter addresses the disposal of carcasses of animals such as cattle, swine, poultry, sheep, goats, fish, and wild birds using anaerobic digestion. This chapter considers anaerobic digestion's economic and environmental competitiveness as a carcass disposal option for either emergencies or routine daily mortalities. This process is suited for large-scale operations, reduces odor, and reduces pollution by greenhouse gases due to combustion of methane. The phases for carrying out these processes and their advantages are presented in detail in the following sections, along with the economics involved.

A simple anaerobic digester installation may cost less than $50 per kg of daily capacity ($22.73 per lb of daily capacity) and construction could be done in less than a month, whereas a permanent installation requires about six months to construct with costs of construction ranging from $70 to $90 per kg of fresh carcass daily capacity ($31.82 to $40.91 per lb of fresh carcass daily capacity). If utilization of the digester is temporary, it is not necessary to use special corrosion resistant equipment, but corrosion will become a problem if the installation is used for several years.

Pathogen containment is a high priority. Though anaerobic digestion is less expensive with mesophilic organisms at 35°C (95°F) than with thermophilic organisms at 55°C (131°F), a temperature of 55°C (131°F) is preferred as the additional heat destroys many pathogens. Many pathogens such as bacteria, viruses, helminthes, and protozoa are controlled at this temperature; however, it is advisable to use additional heat treatment at the end of the process to fully inactivate pathogenic agents capable of surviving in the digester (i.e., spore-formers). Even with an additional heat treatment, inactivation of prions would almost certainly not be achieved.

There are several environmental implications. Anaerobic digestion transforms waste into fertilizer, and from a public relations perspective people generally accept biodigesters. Other concerns include the recycling of nutrients.

Anaerobic digestion has been used for many years for processing a variety of wastes. Research has demonstrated that poultry carcasses can be processed using anaerobic digestion, and this technology has been used commercially. Carcasses have higher nitrogen content than most wastes, and the resulting high ammonia concentration can inhibit anaerobic digestion. This limits the loading rate for anaerobic digesters that are treating carcass wastes.

Anaerobic digestion is a technology worthy of future research. A new process called ANAMMOX—"anaerobic ammonium oxidation"—is proposed for nitrogen removal in waste treatment; this process should be further explored. There is also a need for research regarding how to optimally load carcasses into thermophilic digesters and thereby greatly

reduce costs. Finally, there is a need to identify good criteria to measure pathogen reduction of anaerobic digestion processes.

Section 2 – Historical Use

Anaerobic digestion has been used for centuries. During the 10th century BC, bath water was heated by biogas in Assyria. In the 17th century, Jan Baptista Van Helmont learned that flammable gases could evolve from decaying organic matter, and in 1808 Sir Humphrey Davy determined that the anaerobic digestion of cattle manure produced methane. In 1859, a digestion plant was built at a leper colony in Bombay, India. By 1930, Buswell had identified anaerobic bacteria and the conditions that promote methane production (Biogas Works, 2003; Verma, 2002).

In the domain of anaerobic digestion, facilities built on farms for treatment of manure are perhaps the most common, and six to eight million families have used digesters to produce biogas for cooking and lighting with varying degrees of success. The process experienced a great growth in Europe after World War II because of the demand for energy. The facilities built had a large spectrum of usage in agriculture, industry and municipal waste management. Some facilities in Europe have been in operation for more than 20 years. Today, the technology of anaerobic digestion has been demonstrated and fully commercialized for the treatment of farm, industrial (food), and municipal wastes. There are some technical problems with high-solid concentrations, but several alternatives have been developed that operate with solid concentrations exceeding 30%.

Regarding its application to carcass disposal, anaerobic digestion has been investigated for poultry mortalities (Chen, 1999; Chen, 2000; Chen & Shyu, 1998; Chen & Wang, 1998; Mote & Estes, 1982; Collins et al., 2000). These investigators have demonstrated that poultry carcasses can be processed in anaerobic digesters that are being operated for other waste treatment purposes.

Section 3 – Principles of Operation

3.1 – Introduction

Disposal of carcasses infected, or potentially infected, with pathogenic agents is an important problem in animal production operations. It is necessary to find the best way to eliminate the carcasses without the risk of spreading pathogens. In an outbreak, the farmer may be confronted with a great quantity of carcasses that must be eliminated quickly and safely to prevent the spread of disease.

Anaerobic digestion, sometimes referred to as biomethanization and biodigestion, is one method for the disposal of carcasses. It can eliminate carcasses and produce energy at the same time, but in some cases it is necessary to reduce the size of the carcasses and sterilize them on-site before proceeding with anaerobic digestion. These preliminary measures prevent the risk of spreading pathogens during transportation to a digester and reduce the need for new digesters. If the quantity of carcasses is large, it may be necessary to distribute carcasses between several digesters and to transport them to different locations.

3.2 – General Process Description

Anaerobic digestion involves a transformation of organic matter by a mixed culture bacterial ecosystem without oxygen. It is a natural process that produces a gas principally composed of methane and carbon dioxide. Anaerobic digestion takes place in several steps as shown in Figure 1. Information used to construct Figure 1 was found on the website of Biological Sewage Treatment Tanks (2003) and in Erickson and Fung (1988).

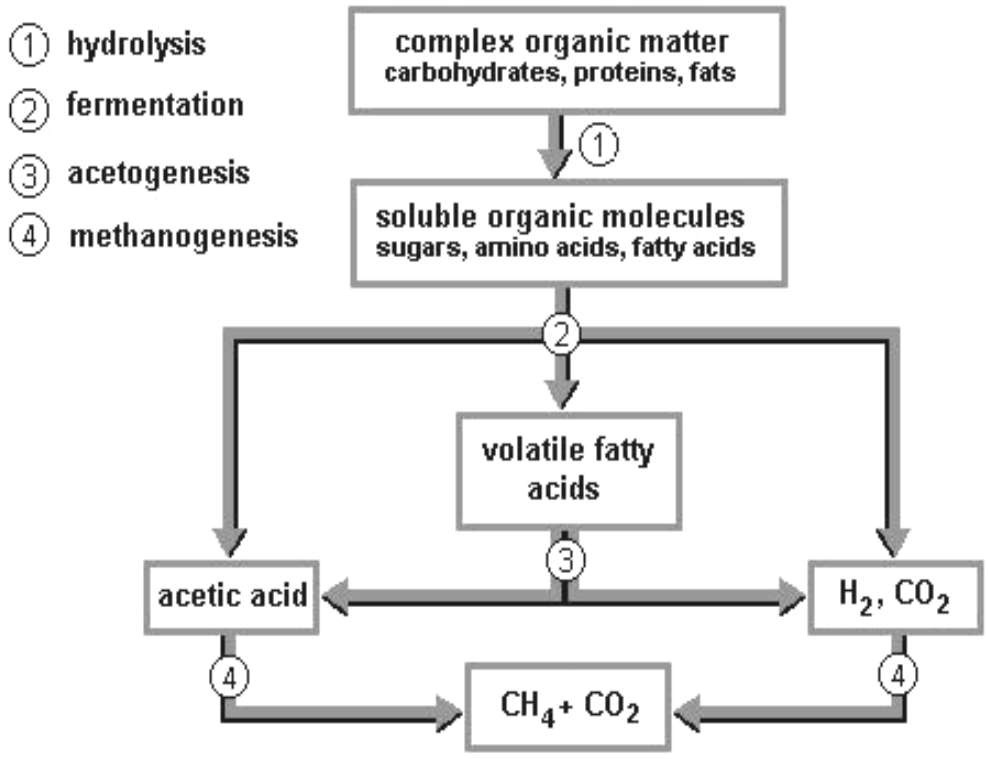


FIGURE 1. Anaerobic digestion pathway (Biological Sewage Treatment Tanks, 2003; Erickson & Fung, 1988).

The first step of anaerobic digestion is the hydrolysis of animal or plant matter. This step breaks down biopolymers and other organic material to usable-sized molecules:

Lipids → Fatty acids

Polysaccharides → Monosaccharides

Protein → Amino acids

Nucleic acids → Purines & Pyrimidines

The second step is the conversion, by acetogenic bacteria, of products of the first step to organic acids, carbon dioxide, and hydrogen. Acetogenic bacteria produce acetic acid; however other organic acids are also produced. The principal organic acids produced are acetic acid (CH_3COOH), propionic acid (CH_3CH_2COOH) and butyric acid ($CH_3CH_2CH_2COOH$). Ethanol (C_2H_5OH) and other products are also produced.

The final step is methanogenesis. Methane and carbon dioxide are produced from acetate, ethanol and other intermediates:

$$CH_3COOH \rightarrow CH_4 + CO_2$$

$$2C_2H_5OH + CO_2 \rightarrow CH_4 + 2CH_3COOH$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

There are several groups of bacteria that perform each step; in total, dozens of different bacterial species are needed to completely degrade matter. The stability of the anaerobic process is very fragile. It is necessary to maintain a balance among the different microbial populations. Significantly, the biogas produced is a natural source of energy, which can be collected and used to generate heat or electricity. The advantage of this method is that it couples the treatment of the waste with energy production (methane).

3.3 – Process Requirements

Equipment

The equipment necessary to generate usable quantities of methane is not simple and requires substantial investment. One could build a digester that would be available for emergency use. This digester could be used to treat animal waste until it is needed for actual carcass disposal. The digestion tank (biodigester) is generally cylindrical for better mixing and the bottom is cone-shaped to facilitate sludge removal. The top can be fixed or floating. A floating top provides expandable gas storage with pressure control but is more expensive and difficult to manage. Most tanks are constructed with concrete and must be strong enough to resist the weight and pressures of the contained liquid. They are often situated at least partially below ground level for better support.

Mixing helps to achieve better distribution of heat and bacteria. Mixing can be accomplished by recirculating the gas collected from the top of the tank or by using mechanical mixers. The mixer is cheaper than recirculation of gas, but it is less efficient. An external heat exchanger or a heat-exchange coil may be necessary to maintain a good temperature in the digester. The heat-exchange coil is better than the external heat exchanger because of the corrosive nature of the liquid and also because the special, non-corrosive materials required in the external heat exchangers are expensive.

Pumps may be necessary to transfer the digester contents and sludge. The high solid content of the sludge requires special solid handling pumps. All piping must be of sufficient size to prevent clogging. To use the methane gas as an energy source requires some gas collection and pressure regulation equipment including the necessary safety devices to prevent explosions. A solid separator is necessary to remove the sludge; the sludge must be dewatered to convert it into useful biosolids. A grinder or other size-reduction equipment may be needed to reduce the size of the pieces of carcass before loading into the digester (Johnston et al., 1998), and a tank can be added to mix water and the solids before loading into the digester.

Supplies and chemicals

In the digester, the pH should be about 7 (between 6.8 and 7.5 is recommended). It may be necessary to use a base or buffer to maintain the pH in the biodigester. The volatile fatty acids and long-chain fatty acids produced by the degradation of fat are inhibitors of methanogenic activity because they decrease the pH. For example, calcium carbonate ($CaCO_3$) can be used as a buffer and calcium hydroxide ($Ca(OH)_2$) can be used to precipitate long-chain fatty acids that are toxic to methanogenic bacteria (Klein, 2002), but there exists a synergism between calcium (Ca^{2+}) and ammonium (NH_4^+). Indeed, potassium, magnesium and calcium increase the toxicity of ammonium more than sodium, which decreases the toxicity (Koster, 1989).

A reactor can be fed with sludge from another installation to provide an inoculation for the start up. According to Massé and Masse (2000), microorganisms in the sludge resulting from municipal wastewater treatment plants perform better than those in the sludge of milk processing plants for initiating anaerobic treatment of slaughterhouse wastewater in a sequencing batch reactor. This may be because the mixed culture from municipal wastewater treatment has the capability to biodegrade a wider range of compounds and wastes.

Utility requirements

The biodigester requires electricity and significant volumes of water. It uses electricity for pumping and mixing. Water requirements can be met by reusing/recycling the water, but water quality requirements of the digestion process must be considered. Moreover, methane may be needed as a fuel for the start-up of the digester before enough biogas is produced to supply the heat requirements of the digester.

Construction and start-up time

The period of construction depends on the time required to collect all material and equipment, as well as the complexity of the digester. Generally, the construction and installation of the equipment requires four to six months and one to three months are needed for the start-up of the digester. Because

of this, carcasses may need to be fed to operating digesters in order to avoid delays associated with start-up.

Capacity

According to Salminen and Rintala (2002), the continuous process appeared to be stable with loadings of up to 0.8 kg volatile solids (VS) per m^3 each day and a hydraulic retention time (HRT) of 50 – 100 days at 31°C (87.8°F). According to Palmowski and Muller (2000), the VS of meat is 225.9 g/kg. To determine the size of digester, it is easier to use 3.6 kg of fresh meat/m^3day (see Appendix A).

Example:

> For 1,000 animals (cattle), each one has a weight of 700 kg (1540 lb) ⇒ 700,000 kg (1,540,000 lb) of beef.
>
> The size of the digester is about 195,000 m^3 with a loading of 0.8 kg VS/m^3d. With a digester volume of 195,000 m^3, the sterilized pieces of the 1,000 animals could be added in one day. In English units, 1,000 animals at 1,540 lbs per animal requires 6,883,000 ft^3 for a loading of 0.05 lb/ft^3 per day of VS.

3.4 – Size-Reduction and Preprocessing Requirement

It is necessary to reduce the size of the carcasses for better heat transfer before sterilization is attempted. If the carcasses are not reduced to a size of less than 5 cm (2.0 inches) in diameter, the heat transfer will take a longer time (Table 1), which of course is not desired. According to Gale (2002), the maximum particle size diameter in a biodigester is 5 cm (2.0 inches), which permits good heat transfer for sterilization of the carcasses and biodigestion.

TABLE 1. Estimated heat transfer times into spherical particles (Gale, 2002).

Particle diameter (cm)	Particle diameter (in)	Time for center to reach 90% of surface temperature (hr)
2	0.79	0.1
20	7.87	10
40	15.75	40

3.5 – Process Options

Dry or wet process

The amount of water or weight fraction of solids is an important factor in the construction of a biodigester. For a wet process, a pre-treatment of organic waste is necessary before loading the waste into the biodigester; conversely, in a dry process the pre-treatment is of less importance.

One-stage wet system

Technical process. The wet process works with a solid fraction between 10 to 15%. Therefore, dilution with water is necessary to obtain total solid contents less than 15%. In the digester, the sludge does not have homogenous consistency because heavy and light fractions form different layers and three phases are generally observed during the process. Bones and parts of the heavy fraction could damage the pump and the foam created by the light fraction could hamper the mixing. Inert solids such as sand must be periodically extracted (Vandeviviere et al., 2002) to assure good functioning of the biodigester. Some reactors use reinjection of product gas in the bottom of the tank to create a loop in the biodigester (Figure 2) and also to obtain better homogenization; other reactors use a simple mechanical mixing process.

This type of process has potential for short-circuiting, as shown in Figure 2. For most pathogens, it is necessary to pasteurize the waste beforehand, as anaerobic digestion of wastes may not be sufficient to control pathogens. The wet system needs equipment like pumps and piping as it involves a large volume of water; this increases the cost and requires additional treatment prior to discharge of the processed waste.

Biological process. Homogenization in the wet system helps to eliminate any special niches where pathogenic bacteria could survive. Ammonium is one of the inhibitors of biodegradation, and its concentration must be kept below 3 g/L (0.187 lb/ft^3). According to Vandeviviere et al. (2002), for certain substances with a carbon to nitrogen (C/N) ratio below 20 and biodegradable VS contents of 60%, the ammonium concentration cannot be brought below this level. Thus, it is beneficial to combine carcasses with other wastes to achieve a higher C/N ratio. The advantages and disadvantages of wet systems are summarized in Table 2.

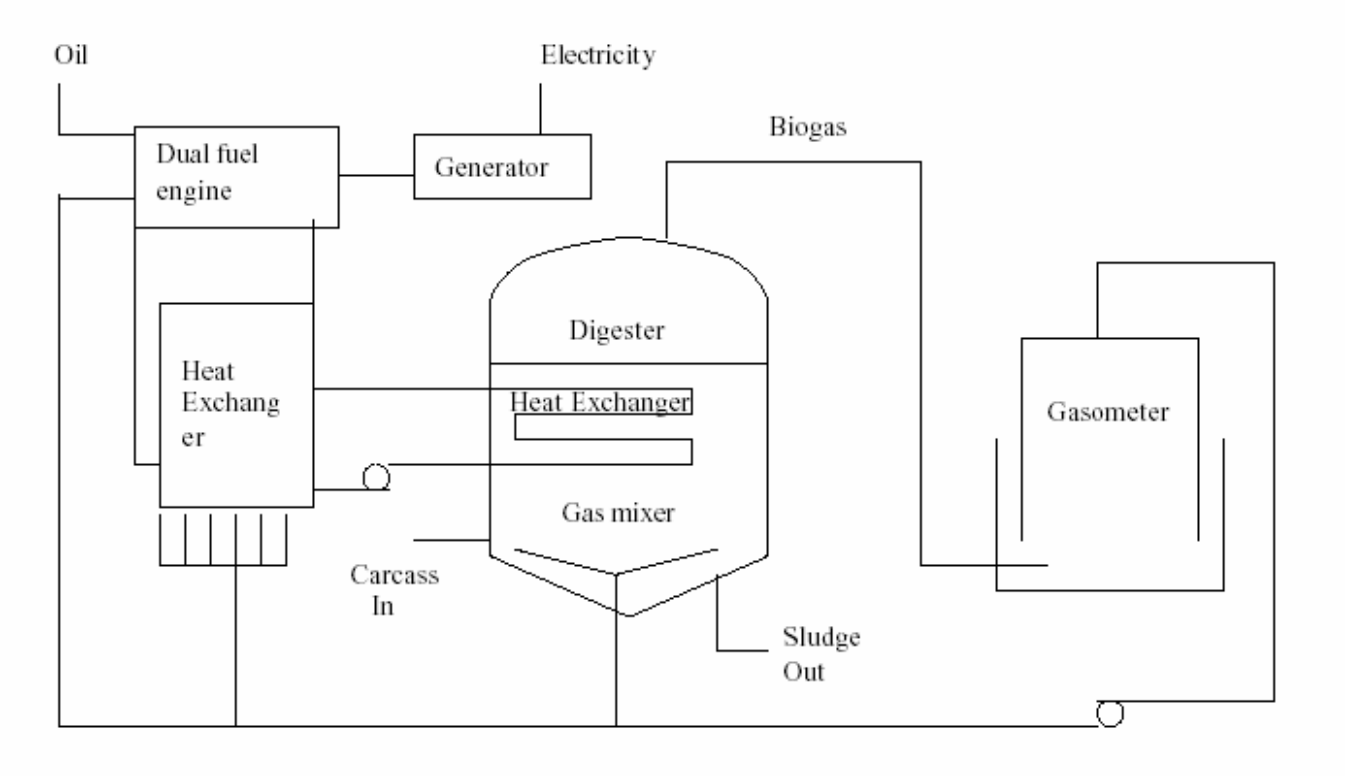


FIGURE 2. The flow diagram of a wet system (Verma, 2002).

TABLE 2. Advantages and disadvantages of a wet system (Vandeviviere et al., 2002).

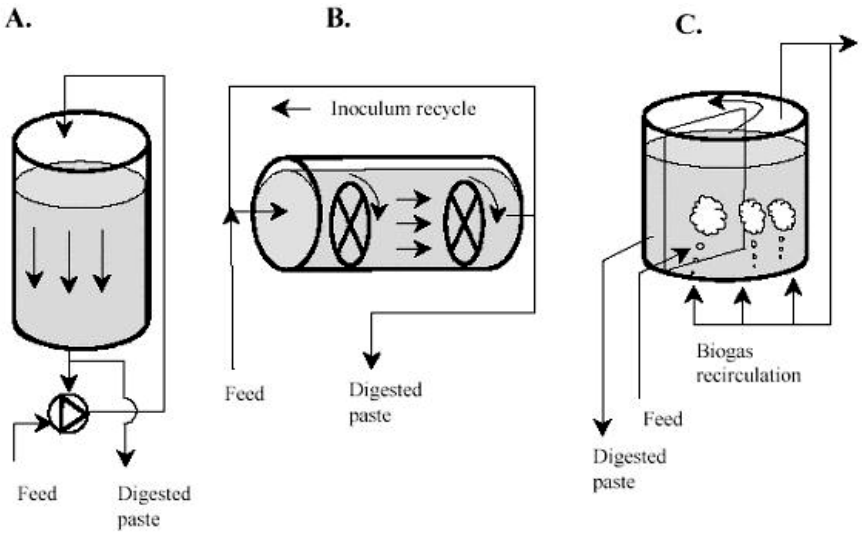
Criteria	Advantages	Disadvantages
Technical	▪ Inspired from known process ▪ Significant operating experience	▪ Short-circuiting reduces efficiency ▪ Sink and float phases (phase separation) ▪ Abrasion with sand
Biological	▪ Dilution of inhibitors with fresh water	▪ Particularly sensitive to shock loads as inhibitors spread immediately in reactor ▪ VS lost with inerts
Economical & Environmental	▪ Equipment to handle slurries is cheaper	▪ High consumption of water ▪ Higher energy consumption for heating large volume

One-stage dry system

Technical process. The dry system works well with solid contents from 20 to 40%. Substances with more than 40% solids must be diluted with fresh water. The dry system is more robust and flexible than the wet system in handling bits such as stone. Generally, the maximum size of particles is 4 cm (1.57 inches). However, mixing in a dry system is more difficult than in a wet system. Three types of homogenization exist in dry systems as shown in Figure 3 (Vandeviviere et al., 2002).

- In the first type, homogenization is achieved via recirculation of the wastes. Wastes are extracted from the bottom of the tank and injected at the top of the reactor for mixing with fresh wastes.
- The second type is the Kompogas process, which uses the same concept of recirculation except that the tank is horizontal and homogenization is aided by slowly rotating impellers inside the reactor.
- The third type is the Valorga system, which is different from the other processes. Here biogas is re-injected every 15 minutes into the bottom of the tank to provide mixing and homogenization.

Biological process. Inhibitors may be less problematic in a dry system than in a wet system. Table 3 lists the advantages and disadvantages of a dry system. The organic loading rate (OLR) mentioned in the table refers to the amount of manure (organic matter) added to the digester each day, divided by the size of the digester. The most common method of measuring organic matter is to use the parameter VS.



A. = Dranco design, **B.** = Kompogas design, **C.** = Valorga design

FIGURE 3. Different digester designs used in a dry system. (Vandeviviere et al., 2002).

TABLE 3. Advantages and disadvantages of a dry anaerobic digestion system (Vandeviviere et al., 2002).

Criteria	Advantages	Disadvantages
Technical	▪ No moving parts inside reactor ▪ Robust (inert materials need not be removed) ▪ No short-circuiting	▪ Wet wastes (<20% total solids) cannot be treated alone
Biological	▪ Less volatile solids loss in pre-treatment ▪ Larger organic loading rate (higher biomass) ▪ Limited dispersion of transient peak concentrations of inhibitors	▪ Little possibility to dilute inhibitors with fresh water
Economical & Environmental	▪ Cheaper pre-treatment and smaller reactors ▪ Complete hygienization ▪ Very small water usage ▪ Smaller heat requirement	▪ More robust and expensive handling equipment (compensated by smaller and simpler reactor)

Batch or continuous

Batch

This type of process may be best suited for carcass disposal events that occur sporadically and are not necessarily a regular phenomenon. In a batch digester, organic material is loaded in the digester and digested for the period of retention time. The retention time depends on temperature and other factors. Once digestion is complete, the effluent is removed and the process is restarted (Figure 4). Generally, it is necessary to have several digesters in a batch process to carry out alternate loading and emptying.

A batch digester is the easiest and cheapest to build. It is also more robust against an inhibitor than a continuous digester, but in a continuous system bacterial flora could become acclimated to the inhibitor by slowly increasing the concentration of the inhibitor. A batch digester produces less gas, has a lower loading rate, and carries a risk of explosion during emptying of the reactor (Vandeviviere et al., 2002).

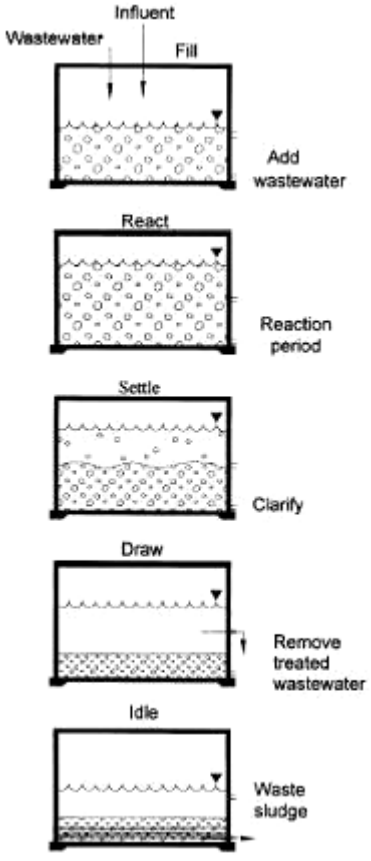


FIGURE 4. Operation of the anaerobic sequencing batch reactor (Massé & Masse, 2000).

In a batch system the contents are continuously mixed, which facilitates good distribution of the nutrients and bacteria. As shown in Figure 5, there exist three types of batch systems:

- Single stage.
- Sequential batch.
- Hybrid batch Upflow Anaerobic Sludge Blanket (UASB) digester.

The single-stage batch system mixes via a recirculation of sludge from the bottom to the top of the digester. The wastes are digested until production of the gas stops. The system is emptied and then loaded again.

The sequential batch system uses two or more reactors. The sludge from the first reactor, which contains a high level of organic acids, is injected into the second reactor. The leachate from the second reactor, after addition of a pH buffering agent, is injected into the first digester. The sludge from the second reactor contains little or no acid as a process called methanogenesis takes place in the second reactor. This type of flow system moves organisms and nutrients between reactors.

The third process is hybrid batch-UASB. It is very similar to the multistage system with two reactors. The system is composed of a simple batch reactor coupled with a UASB reactor. Methanogenesis takes place in the UASB reactor, and can treat liquid effluents with high levels of organic acids at high loading rates (Vandeviviere et al., 2002).

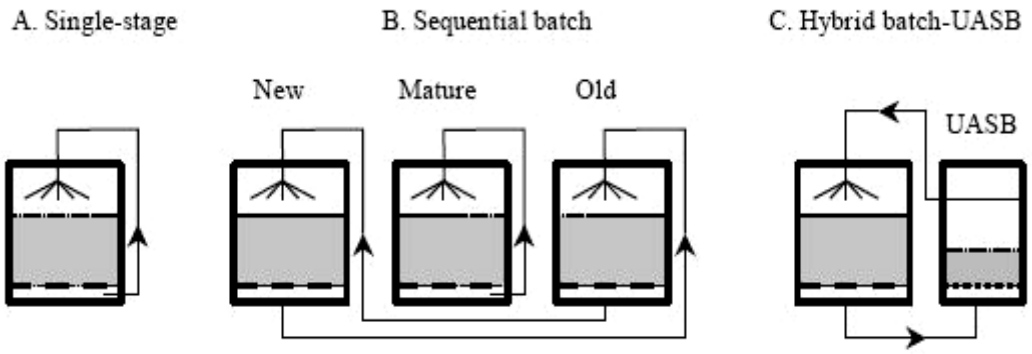


FIGURE 5. Different types of batch reactors (Vandeviviere et al., 2002).

Continuous

In a continuous digester, organic material is constantly or regularly fed into the digester. Generally, the material moves through the digester by pumping. Continuous digesters produce biogas without the interruption of loading the material and unloading the effluent. A continuous system may be better suited for large-scale operations, however the input should be continuous and of consistent composition; a drastic change of input material should be avoided, according to British BioGen (2003).

Mesophilic or thermophilic

The choice of temperature is important. Mesophilic organisms have optimal growth at 35°C (95°F) while thermophilic organisms grow best at 55°C (131°F). Based on the temperature chosen, the duration of the process and effectiveness in destroying pathogens will vary. In mesophilic digestion, the digester is heated to 35°C (95°F) and the typical time of retention in the digester is 15-30 days, whereas in thermophilic digestion the digester is heated to 55°C (131°F) and the time of retention is typically 12-14 days (Vandeviviere et al., 2002).

A mesophilic process tends to be more robust and tolerant to upsets than a thermophilic process, but the gas production is less and the end product may pose a greater pathogen risk if applied directly on fields, whereas a thermophilic digestion system offers higher methane production, faster throughput, and better pathogen and virus "kill." The greater stability of the mesophilic process makes it easier to control. Furthermore, a mesophilic treatment at 38°C (100.4°F) for 15 days reportedly destroys 99.9% of pathogens, while a thermophilic treatment at 55°C (131°F) destroys 99.999% (GVRD, 2000). From a biosecurity perspective, it is better to use a thermophilic process to destroy pathogens in the biodigester and produce a class A end product—that is, a product that could be applied to fields with a minimum risk.

The thermophilic digestion process needs more expensive technology, more energy to maintain its temperature, and a higher degree of operation and monitoring (Vandeviviere et al., 2002). Methanogens, bacteria that produce methane, are more sensitive to variations in temperature than are other bacteria. According to Gunnerson and Stuckey (1986), temperature variations as small as 2°C (3.6°F) can have adverse effects on mesophilic (~35°C or 95°F) digestion, and changes of 0.5°C (0.9°F) affect thermophilic (~55°C or 131°F) digestion.

Alternate processes and configurations

Costs and loading rates depend on the number of phases, as more phases require additional tanks and pumps. As the steps of anaerobic digestion have different optimal operating conditions, better results are obtained by separating the steps. Moreover, it is important that at least one of the phases is a thermophilic phase to destroy the pathogens when the carcasses are processed.

Schafer et al. (2003) have considered several alternate processes. The single digester is the easiest to construct, but a disadvantage of this process is that the feeding of waste has an adverse effect on methane production.

Two-phase digesters can have mesophilic operating conditions in one tank and thermophilic conditions in the other. The anaerobic degradation process starts with an acid phase, in which organic acids are produced (pH below 6), followed by a second phase in which methane gas is produced. There exist several possible combinations between acid-gas phases and mesophilic-thermophilic processes as shown in Figure 6.

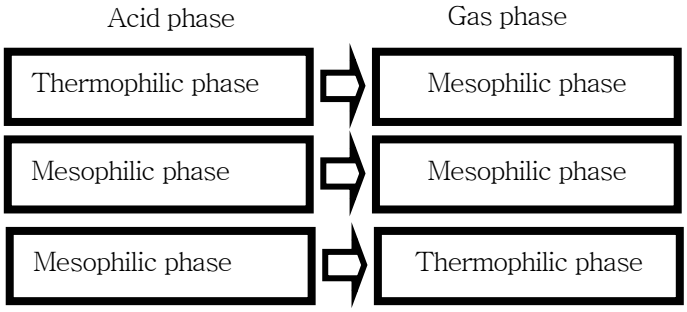


FIGURE 6. Combination of phases used in anaerobic digestion.

It is very important that at least one of the phases is thermophilic to maximize pathogen destruction. An acid-gas phase reduces foaming in the biodigester and increases the rate of matter reduction, but the sludge has high levels of ammonia and probably more hydrogen sulfide is produced during the acid phase (Schafer et al., 2003).

Moreover, thermophilic anaerobic digestion is more sensitive to high ammonium concentration than is mesophilic digestion. This is apparently due to the concentration of free ammonia at high temperatures, as demonstrated by Koster (1989). The balance between the molecular form and ionized form of ammonia depends on temperature. An increase in temperature favors the molecular form, but the molecular form is more toxic than the ionized form. The ammonium concentration is often high during the gas (methane production) phase.

3.6 – End Products

According to the Greater Vancouver Regional District (GVRD, 2000), decades of research on biosolids produced through anaerobic digestion have demonstrated that biosolids can be applied when EPA regulations regarding quality of biosolids and conditions of land application have been met.

Biosolids

After several appropriate treatments, sludge becomes a biosolid that may be used for land disposal. The first treatment of sludge involves thickening of the watery mass. During thickening, biodegradation continues and converts some of the sludge into biogas, which reduces a part of the solid concentration. Several processes are used for thickening; these include gravitation, flotation, and centrifugal concentration. Dewatering of sludge by filtration or centrifugation may follow thickening. Together, these treatments reduce disposal costs by reducing the quantity of biosolid. Furthermore, the water-eliminated liquor may be treated before discharge and used for agricultural purposes. With the addition of lime, chlorine, or heat, biosolids may be stabilized to reduce both odor and the number of pathogens present (Newton, 1985).

There are biosolid regulations designed to prevent the risk of pathogens. Only biosolids of class A and B may be applied to land, with class A biosolids being subject to more restriction than class B biosolids (GVRD, 2000). Regulation-compliant biosolids may be sold and used as soil amendments; unsafe biosolids should be destroyed, perhaps by incineration. When containment of a pathogen is of high priority, it is important to determine whether the pathogen is present in the anaerobic digester and/or the biosolids. If carcasses are sterilized following size reduction, the material delivered to the digesters should be free of pathogens; however, it is desirable to also check the digester broth for pathogens.

Class A standards for pathogen reduction require a fecal coliform density of less than 1,000 MPN (most probable number) per gram dry weight, or a *Salmonella* density of less than 3 MPN per 4 grams dry weight. These standards may be met by a specific time-temperature combination treatment (55°C [131°F] for 20 days).

Class B standards require the density of fecal coliforms to be less than two million per gram dry weight. Class B standards are met by mesophilic (38°C [100.4°F]) processing of the biosolids.

Liquor

Liquor produced from anaerobic digestion can be used as a liquid fertilizer because of its wide range of nutrients; however, if it has a low level of nutrients and a high level of water, it could simply be used in irrigation. According to British BioGen (2003), liquor can be used for "fertigation" (a combination of fertilizer and irrigation) on agricultural lands, but it cannot be used in greenhouses as it contains some particles that block feeder pipes. Sometimes, the liquor can be bottled and sold like fertilizer—but only if it is indeed safe.

Methane

Methane from anaerobic digestion can be used for the production of heat, which could be used to maintain a proper temperature in the digester or to heat a local farm or factory. Methane can also be used for the production of electricity. Such use of biogases reduces the consumption of fossil fuels and may reduce the cost of electricity at the particular digestion facility. If produced in sufficient quantities, methane-produced electricity can be sold to local energy distribution networks.

3.7 – Economics

Chen (1999 and 2000) and Chen and Shyu (1998) have used anaerobic digestion for disposal of poultry carcasses. According to Chen and Shyu (1998), the continuous process at 35°C (95°F) requires optimization to become competitive with other biological treatment processes used to destroy carcasses. Process optimization may allow a larger loading rate, which would reduce treatment costs. Anaerobic digestion at 35°C (95°F) is less expensive than at 55°C (131°F), but digestion at 55°C (131°F) is preferable as the additional heat destroys pathogens.

The cost of installation depends on the materials of construction. There are digesters composed of polyethylene that cost between \$7 per m^3 (in Vietnam) and \$30 per m^3 (in Colombia) (Bui Xuan An et al., 2003). These figures (\$7 per m^3 and \$30 per m^3) would correspond to \$2 per kg (\$0.90 per lb) and \$8.50 per kg (\$3.86 per lb) of carcass material, respectively. These polyethylene digesters have a low capacity (5-6 m^3), and it may not be possible to adapt them for disposal of carcasses. Appendix B provides examples of the determination of the cost of installation.

An anaerobic digester could be constructed by digging a simple trench covered with a liner. The broth contents should be covered to maintain anaerobic conditions. If utilization of the digester is temporary, it is not necessary to use special, corrosion-resistant equipment. Indeed, corrosion of a digester may become a problem only if an installation is used for several years. The cost of this simple type of installation is probably less than $50 per kg ($22.73 per lb) of daily capacity and the construction could be done in less than a month.

For a permanent installation, concrete construction of the digester takes about six months. Consequently, this type of installation requires construction well in advance of an emergency situation. It is important to choose a site that would minimize transport of carcasses from the point of origin to the digester. Since the occurrence of mortalities may be sporadic, it would be advantageous to use the digester for other substances like manure or municipal waste. Such utilization of the digester would allow more rapid recuperation of costs. The average price of construction is between $70 and $90 per kg ($31.82 and $40.91 per lb) of fresh carcass daily capacity (White and Van Horn, 1998; Boehnke et al., 2003) (see Appendix B).

Section 4 – Disease Agent Considerations

4.1 – Pathogen Containment

Pathogen containment must be a high priority in carcass management (European Commission, 2003). The list below is not exhaustive, but does provide a good representation of different pathogenic agents encountered in animal operations. While several authors agree that laboratory-grade pathogens are often less hardy than naturally-occurring strains (Couturier and Galtier, 2000), the results below are representative.

Bacteria

Results of laboratory studies on the destruction of bacteria at different temperatures are shown in Table 4.

All pathogenic bacteria listed are destroyed more rapidly at 53°C (127.4°F) than at 35°C (95°F); consequently, thermophilic digestion is advised. Some undesirable thermophilic bacteria can survive anaerobic digestion, however. For example, *Bacillus cereus* and *Bacillus anthracis* can survive temperatures of 53°C (127.4°F) and be transmitted by biosolid dust to infect the human eye. To prevent such risks from thermoresistant bacteria, it is important to add an additional heat treatment if such organisms are present.

TABLE 4. Results of laboratory studies on the destruction of bacteria at different temperatures (Couturier & Galtier, 2000; Gale, 2002).

Organism	T90[a] at 35°C or 95°F (days)	T90 at 53°C or 127°F (days)
Salmonella typhimurium	2.4	0.7
Salmonella Dublin	2.1	0.6
Escherichia coli	1.8	0.4
Erysipelothrix rhusiopathiae	1.8	1.2
Staphylococcus aureus	0.9	0.5
Mycobacterium paratuberculosis	6	0.7
Coliforms	3.1	-
D-streptococci	7.1	-
Streptococcus faecalis	2	1
Clostridium perfringens	No reduction	No reduction
Bacillus cereus	No reduction	No reduction

[a]T90 = the time in days necessary to destroy 90% of bacteria.

Viruses

Among viruses, the parvovirus is the most resistant. Therefore, some authors advise using parvovirus as

a criterion for virus destruction. Unfortunately, parvovirus is not a good surrogate for animal viruses (Couturier & Galtier, 2000). Results of laboratory studies on the destruction of viruses at different temperatures are shown in Table 5.

TABLE 5. Results of laboratory studies on the destruction of viruses at different temperatures (Couturier & Galtier, 2000).

Organism	Inactivation time at 35°C (95°F)	Inactivation time at 55°C (131°F)
Porcine flu	>24h	1h
Parvovirus porcine	21 weeks	8 days
Bovine virus diarrhea	3h	5 minutes
Infectious bovine rhinotracheitis	24h	10 minutes
Aujesky's disease virus	5h	10 minutes
Classical swine fever virus	4h	Some seconds
Transmissible gastroenteritis virus (TGE virus)	24h	30 minutes

Helminthes

Helminthes include a vast number of worm species, most of which are parasitic. Worms are present in manure and some animals are affected by helminthes. Information on the inactivation of helminthes is provided in Table 6.

TABLE 6. Results of laboratory studies on the destruction of helminthes (worms) at different temperatures (Couturier & Galtier, 2000; Gale, 2002).

Organism	Inactivation time at 35°C (95°F)	Inactivation time at 53°C (127°F)
Egg of gastro-intestinal worms of bovine	2 days	1-4h
Egg of nodular worm of the pig	6-8 days	1-4h
Egg of Ascaris	21-35 days	20-50 minutes

Protozoa

According to the GVRD (2000, p. 10), "it is highly improbable that protozoan cysts could survive conditions capable of destroying helminth eggs."

4.2 – Risk of Contamination

If the end products of anaerobic digestion (biosolids) are applied to land without pathogens being sufficiently reduced, the pathogens may pose a risk of contamination. Human beings and animals can be contaminated after being exposed to variable quantities of pathogens, as shown in Table 7. The infective dose depends on the type of pathogen and health of the host. Indeed children, older people, and people with compromised immune system are at greatest risk.

TABLE 7. Minimal infective doses of pathogens (GVRD, 2000).

Organism	Minimal infective dose
Salmonella sp.	10^2 to 10^{10}
Shigella sp.	10 to 10^2
Escherichia coli	10^4 to 10^{10}
Giardia lamblia	1 cyst
Cryptosporidium parvum	10 cysts
Ascaris lumbricoides	1-10 eggs

Generally, sludge accumulates in the bottom of the digester. Consequently, all pathogen agents capable of surviving in the digester could still be found in the end product several months after the introduction of pathogens in contaminated carcasses.

Bovine spongiform encephalopathy (BSE), or "mad cow disease," can survive anaerobic digestion. This disease is due to a protein, called a prion, which causes a fatal degenerative disorder of the brain. Prions are highly resistant to many treatments; only two available technologies are reported to inactivate prions: incineration and alkaline hydrolysis (Jennette, 2002). *Bacillus cereus* and *Clostridium* can also survive thermophilic digestion (Couturier & Galtier, 2000) and should receive additional heat treatment.

As an alternative to thermal treatment of the end product, carcasses could be disinfected prior to loading into the digester. Such a pre-treatment may eliminate the need for post-processing disinfection, but it also might inhibit anaerobic digestion if it affects the bacterial flora of the digester. Human beings and animals can be exposed to risk of pathogens by several pathways. These different pathways can be by direct or indirect contact.

Direct contact

Direct contact occurs when a person or animal is directly in contact with the biosolid. Generally, this contact takes place at the digester or on the field where the biosolids have been applied recently or from the transport of dust. The field should be left free of cultivation or grazing during a specific period and its access should be limited. The survival time of different organisms in the soil depends on species and conditions as shown in Table 8.

TABLE 8. Estimated survival times of pathogens in soil and on plant surfaces (GVRD, 2000).

	Soil		Plants	
Pathogen	**Absolute Maximum**	**Common Maximum**	**Absolute Maximum**	**Common Maximum**
Bacteria	1 year	2 months	6 months	1 month
Viruses	1 year	3 months	2 months	1 month
Protozoan cysts	20 days	2 days	5 days	2 days
Helminth eggs	7 years	2 years	5 months	1 month

Jakubowski (1988), Sorber and Moore (1986), and Sobsey and Shields (1987) have investigated the fate of pathogens and viruses in soil. Knowledge of the survival time is useful to identify a specific period during which the field should not be accessed or used for cultivation or breeding.

Indirect contact

Indirect contact is more difficult to anticipate. It can be due to pathogens on crops grown on the field used for land application, or via use of water contaminated by runoff from land application. Organism movement depends on several factors including soil, rainfall, and sources of transport like birds, mice, or airborne dust. It is important to consider a buffer zone around a digester or field where biosolids are applied.

Personnel

Some workers are directly in contact with carcass digesters and sludge. There are two types of risk; the first is the toxic risk of gases such as hydrogen sulfide produced by biodigestion and the second is microbiological risk. Certain pathogens that affect animals could also affect human beings.

Section 5 – Implications to the Environment

There are several environmental advantages to anaerobic digestion. The process reduces greenhouse gas problems, decreases the consumption of fuel, and transforms waste into fertilizer. The consumption of water is a problem in dry areas; however, water from the process can be used for irrigation.

From a public relations perspective, people generally accept biodigesters. However, they should still be constructed far from residential areas for reasons of biosecurity and to minimize odor problems.

Section 6 – Advantages and Disadvantages

Anaerobic digestion offers both advantages and disadvantages, which are summarized in Table 9.

TABLE 9. Advantages and disadvantages of anaerobic digestion.

Advantages	Disadvantages
Couples the treatment of waste and production of energy	Cost of construction is expensive
Reduction of odors	Sludge disposal is a problem in some locations
Suited for large-scale operations	Larger than other installations such as lactic acid fermentation
Methane is used in place of fossil fuels	Difficulty of storage of gas (corrosive)
Reduces pollution by greenhouse gases by combusting methane	Significant consumption of water
Recycle effluent in fertilizer	Storage of fertilizer is difficult
Reduces chemical and biological oxygen demand, total solids and volatile solids of the carcass	Problem of management of the sludge
Destroys, or reduces to acceptable levels, coliform bacteria, pathogens, insect eggs and internal parasites	Does not destroy all pathogens: ▪ Prions (e.g., mad cow disease, chronic wasting disease) ▪ Thermo resistant bacteria (e.g., *Bacillus cereus*)

Section 7 – Critical Research Needs

Anaerobic digestion is well known for its application to the treatment of industrial, municipal, and agricultural waste. Nevertheless, it is rarely used for the disposal of carcasses. In fact, only a few studies are available about anaerobic digestion and carcass disposal. Areas of research regarding anaerobic digestion and carcass disposal are enumerated below.

1. Consider how to (and whether to) extend anaerobic digestion to large-animal carcass disposal.

Past research has demonstrated that poultry carcasses can be processed in anaerobic digesters. For larger animals, size reduction seems imperative. While it may be possible to load digesters with whole cattle, there are no data on either digester performance or pathogen management. Some research has been reported on the composting of large animals (Anonymous, 2003). Research is needed to develop the anaerobic digestion process if it is to be seriously considered. There are many manure management operations where manure is treated in an anaerobic digester that consists of a covered pond that may be lined. The wastes flow into the pond from the feeding area. Carcass mortalities could be flushed into the digester through the same inlet system; however, methods to feed carcass waste need to be investigated further.

2. Study how to eliminate ammonium during the process.

   Carcasses seem to have great methanogenic potential, but in reality deamination of protein generates a high concentration of ammonium, which inhibits methanogens. The maximum concentration of ammonium tolerated by methanogens after adaptation is about 1.5 to 3 g/l, and the free ammonia level must be kept below 80 mg/l (Gunnerson & Stuckey, 1986). This maximal concentration depends on several factors such as type of process and conditions required for digestion. Several means have been considered for solving this ammonium problem. A new process called "ANAMMOX" might be used to eliminate ammonium (Dongen, 2003). ANAMMOX, which stands for "anaerobic ammonium oxidation," is a new method of nitrogen-removal in wastewater treatment. The process is patented; licenses may be obtained from Paques B.V. (2003), which installed the first reactor in 2002. Research to develop this process for carcass disposal is needed. Blending carcasses with other wastes can also reduce the concentration of ammonia in the digester. If suitable wastes are available, the desired carbon to nitrogen (C/N) ratio can be obtained by blending. When carcasses are added to an operating digester, the total capacity of the digester and the C/N ratio should be considered. Research is needed to establish optimum loading for a thermophilic digester, and for a digester equipped with a system of ammonium removal. Indeed, the tank is the most expensive part of the biodigester and if the loading rate could be increased, the cost would greatly decrease.

3. Consider how to alleviate problems with fats in anaerobic digestion.

   Fats degrade to long-chain fatty acids, which inhibit methanogens.

4. Identify appropriate criteria to measure pathogen reduction.

   In US Environmental Protection Agency regulations, the criterion chosen is the reduction of fecal coliforms. Fecal coliforms are reduced at rates generally comparable to many pathogens. However, Couturier and Galtier (2000) note that the fecal Streptococci are a better indicator of pathogen destruction than fecal coliforms under thermophilic conditions. For carcass disposal, there is a need to measure pathogen reduction for the organism of concern (Burtscher & Wuertz, 2003).

References

Anonymous. (2003). Hog Mortality Composting (Manual). Denver, Colorado: Colorado Governor's Office of Energy Management and Conservation.

Biogas Works. (2003). http://www.biogasworks.com

Biological Sewage Treatment Tanks. (2003). http://www.biotank.co.uk/

Boehnke, J., Eidam, M., & Pierson, J. (2003). Biodigestion of animal carcasses (Department of Chemical Engineering report). Manhattan, Kansas: Kansas State University.

British BioGen. (2003). Anaerobic Digestion of farm and food processing residues (Good Practice Guidelines). http://www.britishbiogen.co.uk/gpg/adgpg/adgpg.pdf

Bui Xuan An, Rodríguez, L., Sarwatt, S.V., Preston, T.R., & Dolberg, F. (2003). Installation and performance of low-cost polyethylene tube biodigesters on small-scale farms. http://www.fao.org/ag/aga/agap/frg/feedback/war/W5256t/W5256t06.htm

Burtscher, C., & Wuertz, S. (2003). Evaluation of the use of PCR and Reverse Transcriptase PCR for Detection of Pathogenic Bacteria in Biosolids from Anaerobic Digesters and Aerobic Composters. *Applied and Environmental Microbiology, 69* (8), 4618 – 4627.

Chen, T.-H. (1999). Anaerobic digestion of poultry mortalities in a modified LB-UASB. *Journal of Environmental Science and Health, B34* (3), 527-547.

Chen, T.-H. (2000). Evaluation of anaerobic system for treating poultry mortalities. *Transaction of the ASAE, 43* (6), 1781-1788.

Chen, T.-H., & Shyu, W.-H. (1998). Chemical characterization of anaerobic digestion treatment of poultry mortalities. *Bioresource Technology, 63* (1), 37-48.

Chen, T.-H., & Wang, J.-C. (1998). Performances of mesophilic anaerobic digestion systems treating poultry mortalities. *Journal of Environmental Science and Health, B33* (4), 487-510.

Collins, A.R., Murphy, J., & Bainbridge, D. (2000). Optimal loading rates and economic analyses for anaerobic digestion of poultry waste. *Journal of the Air & Waste Management Association, 50* (6), 1037-1044.

Couturier, C., & Galtier, L. (2000). Etat des connaissances sur le devenir des germes pathogens et des micropolluants au cours de la methanisation des dechets et sous-produits organiques (Programme ADEME, N° contrat: 9893024). Report: http://www.solagro.org/site/im_user/034impacts.pdf. Annex: http://www.solagro.org/site/im_user/034annexes_sanitaire.pdf

Dongen, V.U. (2003). The combined SHARON ANAMMOX process (TU Delft Department of Biotechnology publication). http://www.bt.tudelft.nl/r_proj/mic/P_Dongen.htm

Erickson, L.E., & Fung, D.Y.C. (1988). Handbook on Anaerobic Fermentations, Marcel Dekker, New York. 850p.

European Commission. (2003). Opinion on six alternative methods for safe disposal of animal by-products. http://europa.eu.int/comm/food/fs/sc/ssc/out352_en.pdf

Gale, P. (2002). Risk assessment: use of composting and biogas treatment to dispose of catering waste containing meat (Final Report to the Department for Environment, Food and Rural Affairs). http://www.defra.gov.uk/animalh/by-prods/publicat/report5.pdf

Gunnerson, C.G., & Stuckey, D.C. (1986). Anaerobic digestion: principles and practice of biogas systems (World Bank Technical Paper No. 49). Washington, DC: World Bank.

GVRD. (2000, May). The Biosolids Report (Report No. 1). http://www.gvrd.bc.ca/ and http://www.nutrifor.com/pdfs/BR_pathogens.pdf

Jakubowski, W. (1988, May). Ascaris ova survival in land application conditions (unpublished US EPA Administrator's Item Deliverable 2799).

Jennette, P.J. (2002, Spring). Medical waste management at Cornell's college of veterinary medicine. http://www.cayugalake.org/newsletter/spring/2002/spring2002.pdf. *Cayuga Lake Watershed Network – Network News,* 6-7.

Johnston, L.J., Robinson, R.A., Clanton, C.J., Goyal, S.M., Ajariyakhajorn, C., & Heilig, D.M. (1998). Homogenization for disposal of dead piglet carcasses. *Applied Engineering in Agriculture, 14* (2), 183-186.

Klein, J. (2002). Anaerobic wastewater treatment – The anaerobic digestion of lipids (Tampere University of Technology Department of Environmental Engineering seminar publication). http://studweb.studserv.uni-stuttgart.de/studweb/users/uws/uws28755/jck/lipiddigestion.pdf

Koster, I.W. (1989). *Toxicity in anaerobic digestion, with emphasis on the effect of ammonia, sulfide and long-chain fatty acids on methanogenesis*. Doctoral dissertation, Wageningen Agricultural University, Wageningen, The Netherlands.

Massé, D.I., & Masse, L. (2000). Treatment of slaughterhouse wastewater in anaerobic sequencing batch reactors. http://www.engr.usask.ca/societies/csae/c9917.pdf. *Canadian Agricultural Engineering*, *42* (3), 131-137.

Mote, C.R., & Estes, R.D. (1982). Solids removal rates and energy requirements for dead poultry decomposition in heated septic tanks. *Poultry Science*, *61* (10), 1956-1961.

Newton, J. (1985). Special report: Sludge treatment and disposal processes. http://www.genesyst.com/Independent_Study/Special%20Report,%20Sludge%20Treatment%20and%20Disposal%20Processes.pdf. *Pollution Engineering*.

Palmowski, L., & Muller J. (2000). Influence of the size reduction of organic waste on their anaerobic digestion. http://www-public.tu-bs.de:8080/~jom/Veroeffe/Barcel699ss.pdf. *Water Science and Technology*, *41* (3), 155-162.

Paques B.V. (2003). http://www.paques.nl/

Salminen, E.A., & Rintala, J.A. (2002). Semi-continuous anaerobic digestion of solid poultry slaughterhouse waste: effect of hydraulic retention time and loading. *Water Research*, *36* (13), 3175-3182.

Schafer, P.L., Farrell, J.B., Newman, G., & Vandenburg, S. (2003). Advanced anaerobic digestion processes. *Water Environment & Technology*, *15* (5), 38-45.

Sobsey, M.D., & Shields, P.A. (1987). Survival and transport of viruses in soils: model studies. In V.C. Rao and J.L. Melnick (Eds.), *Human Viruses in Sediments, Sludges and Soils*. Boca Raton, Florida: CRC Press.

Sorber, C.A., & Moore, B.E. (1986). Survival and Transport of Pathogens in Sludge-Amended Soil: a critical literature review (Report No.: EPA/600/2-87/028). Cincinnati, Ohio: EPA Office of Research and Development.

Vandeviviere, P., De Baere, L., & Verstraete, W. (2002). Types of anaerobic digester for solid wastes. In J. Mata-Alvarez (Ed), *Biomethanization of the organic fraction of municipal solid wastes* (pp. 111-137). London: IWA Publishing.

Verma, S. (2002). *Anaerobic digestion of biodegradable organics in municipal solid wastes*. http://www.seas.columbia.edu/earth/vermathesis.pdf. Thesis, Columbia University, New York.

White, J.G., & Van Horn, C. (1998). Anaerobic digester at Craven farms — A case study. http://www.energy.state.or.us/biomass/digester/craven.pdf. Salem, Oregon: Oregon Office of Energy.

Appendices

Appendix A – Determination of Value 3.6 kg of Fresh Meat/m^3 (0.224 lb of Fresh Meat/ft^3)

According to Salminen and Rintala (2002), the process appeared stable with loadings of up to 0.8 kg VS/m^3.d and a HRT of 50–100 day at 31°C (87.8°F). Moreover according to Palmowski and Muller (2000) VS of the meat is 225.9 g/kg of fresh meat.

Calculation of loading: 0.8/0.2259 = 3.54 kg

The value given for 3.6 kg of fresh meat/m^3 (0.224 lb of fresh meat/ft^3) had been rounded up to consider the insoluble part of carcass like bone.

Example: For 1,000 beef cattle, each one has a weight of 700 kg ⇒ 700,000 kg of beef

The size of digester is 197,667 m^3 with 3.54 kg/m^3.

The size of digester is 194,444 m^3 with 3.6 kg/m^3.

Appendix B – Determination of Price of Installation

The price of concrete installation is extrapolated from the installation for manure. These two installations are equipped by:

Equipment	Farm 1 Cost[a]	Farm 2 Cost[b]
Mix tank	73,000	15,000
Manure storage	13,130	
Manure pump	9,800	7,000
Piping	520	475
Digester	132,000	68,178
Gas and water transmission	3,600	3,338
Engine generator and building	52,000	47,026
Solids separator	38,000	27,000
Solids storage building	38,000	37,000
Startup propane	5,700	4,416
Engineering	27,000	20,000
Expenses	4,000	4,000
Total Cost	$400,000	$320,000
Digester Size	1,325 m^3	1,210 m^3
Capacity (size * 3.6 kg/m^3)	4,770 kg	4,356 kg
Cost per kg of capacity	$84/kg ($38.18/lb)	$72/kg ($32.72/lb)

[a]Boehnke et al., 2003

[b]White and Van Horn, 1998