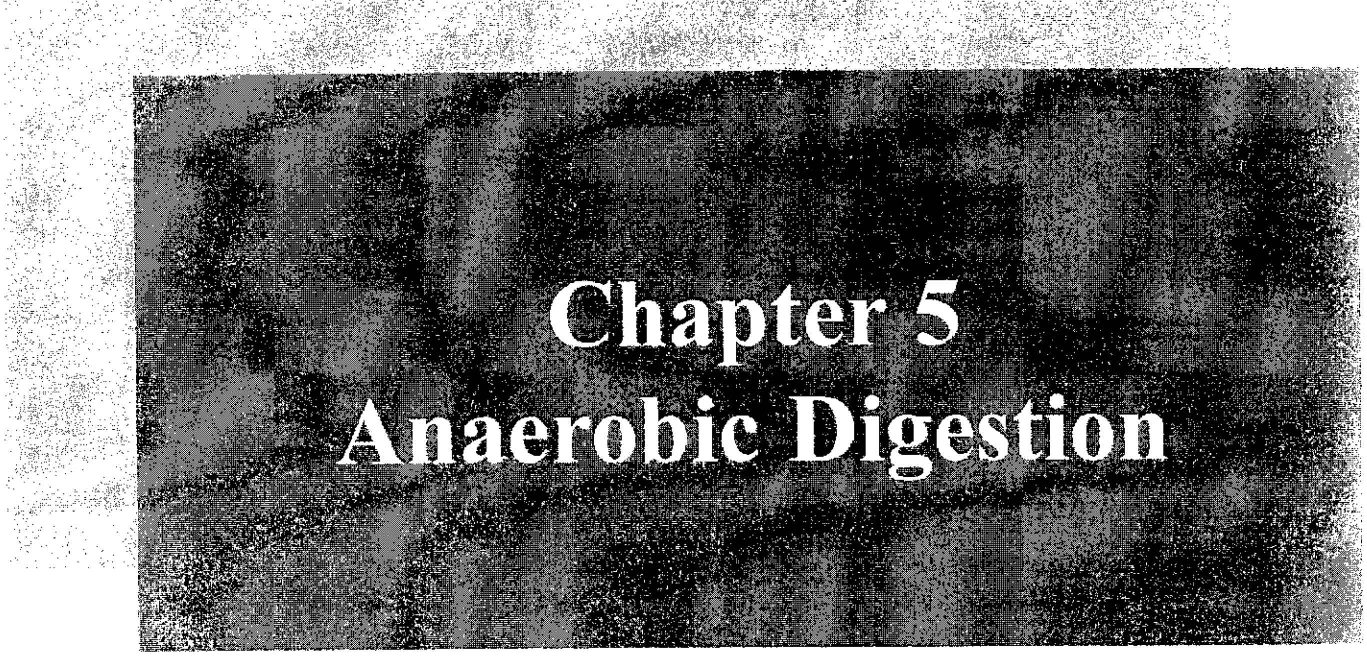

Chapter 5 Anaerobic Digestion

5.1 INTRODUCTION

Anaerobic digestion is one of the most common processes that occur in nature. Anaerobic digestion is driven by naturally occurring anaerobic microorganisms and takes place in an oxygen-free environment. The anaerobic microorganisms convert organic matter into a mixture of **methane**, carbon dioxide, and other **biogases.** Anaerobic digestion can be used to **stabilize** manure, reduce odor emissions, and produce energy and a nutrient-rich **soil amendment**, as depicted in **Table 5.1.**

Table 5.1: Potential anaerobic digestion benefits.

Chapter Number	Chapter Name	Treatment Process	Reduce Nitrogen	Reduce Phosphorus	Reduce Biochemical Oxygen Demand	Stabilize Manure	Reduce Manure Volume	Reduce Pathogens	Reduce Manure Gases	Reduce Odor	Reduce Ammonia Volatilization	Operate at Low Temperatures	Minimal Footprint	Low Energy Requirement	Create Biogas	Create Value-Added Products
5	Anaerobic Digestion	Mixed reactor				√		√	√	√					√	
		Fixed film				√		√	√	√					√	
		Plug flow				√		√	√	√					√	
		Ambient lagoon				√		√	√	√					√	
		Heated mixed lagoon				√		√	√	√		√			√	

Anaerobic: An oxygen-free environment or requiring an oxygen-free environment to survive.

Methane: A gas (CH_4) produced when anaerobic bacteria decompose organic matter. Methane is a strong greenhouse gas. Methane can be used as fuel.

Biogas: A combustible gas produced during the anaerobic decomposition of organic material. Biogas is primarily composed of methane, carbon dioxide, and hydrogen sulfide.

Stabilization: A microbial process that results in material that cannot be easily decomposed.

Soil amendment: Compounds used to build and maintain the physical properties of soil.

Anaerobic bacteria are among the oldest life-forms on earth. Anaerobic bacteria exist naturally at the bottom of ponds and swamps, in the digestive tracts of large animals and termites, and most other airless places. If manure is placed in a container of almost any size or shape and the temperature is above freezing and below 66° C (150° F) anaerobic microorganisms will decompose the organic matter and produce biogas (Miner et al., 2000).

Anaerobic digestion is used extensively in the treatment of human waste. The most common form of anaerobic digestion is the household septic tank. Anaerobic digestion is also used in municipal wastewater treatment plants. Anaerobic digestion is used widely in other parts of the world for manure treatment, in particular where manure management has been considered a serious problem for a longer period of time, land bases are smaller, and energy costs are higher relative to personal income than in the United States. The first anaerobic digesters in the US were installed in the 1970's at dairies to produce energy during the energy crisis, but when energy prices stabilized anaerobic digestion fell out of favor. In recent years, anaerobic digesters have regained popularity in the US. As environmental regulations and odor issues continue to gain attention, the number of operating farm-scale digesters in the US increased by 30 percent from 2000 to 2002 (US EPA, 2003). Anaerobic digestion may be an effective treatment option for medium to large farms producing relatively dry manure and wishing to decrease odors or to generate biogas.

5.2 Advantages and Disadvantages of Anaerobic Digestion

Anaerobic digestion is not the magic bullet for solving manure management problems, and is not appropriate for all climates, manures, and management styles. A system of treatment processes is always more effective than relying on a single unit process; anaerobic digestion may be successfully paired with several other unit processes. **Table 5.2** summarizes some of the advantages and disadvantages of anaerobic digestion as compared to aerobic digestion.

The subject of anaerobic digestion use on farms, especially on confined animal feeding operations (CAFOs), is a much-debated issue. As with any treatment technology, the complex environmental, social, and economic impacts of anaerobic digestion must be

Table 5.2: Advantages and disadvantages of anaerobic processes compared to aerobic processes (Metcalf and Eddy, 2003).

Advantages	Disadvantages
May require less energy	Nitrogen and phosphorus removal is not possible
Less biomass produced	Longer start-up time required
Fewer nutrients required in feedstock	May require additives to meet alkalinity needs
Methane is a potential energy source	More sensitive to low temperatures
Smaller reactor volume required	More susceptible to toxic substances
Elimination of off-gas air pollution	Potential for production of odors
Rapid response to feedstock after long idle periods	Potential for production of corrosive gases
	Potential for production of explosive gases

assessed before an informed decision as to whether to implement the unit can be made. Compared to other alternative manure treatment technologies, the role of anaerobic digestion as a tool in effective manure management and whole-farm plans is hotly contested. While this report deals solely with how, why, and where alternative manure treatment technologies work, information and viewpoints regarding the economic and policy impacts of anaerobic digestion can be found at:

The Economics and Feasibility of Electricity Generation Using Manure Digesters on Small and Mid-size Dairy Farms by Aashish Mehta, PhD, Department of Agricultural and Applied Economics Energy Analysis and Policy Program at University of Wisconsin-Madison (www.uwex.edu/uwmril/pdf/RuralEnergyIssues/renewable/Biogas_Economics_Mehta.pdf),

AgStar, a joint program of the United States Environmental Protection Agency, the United States Department of Agriculture, and the United States Department of Energy (www.epa.gov/agstar), and

Mother Lode Chapter of the Sierra Club (http://motherlode. sierraclub.org/MethaneDigestersSIERRACLUBGUIDANCE.htm).

5.2.1 Advantages

Odor reduction is often cited as a reason to implement anaerobic digestion. An impermeable barrier is constructed between the manure and the atmosphere in order to create the oxygen-free anaerobic environment. This barrier generally prevents the release of odorous compounds from the manure treatment facility. Anaerobic digestion may reduce odor emissions by as much as 97 percent (Frame et al., 2001).

Anaerobic digestion reduces the solids volume by 50 to 60 percent (Frame et al., 2001). These solids may be used as a soil amendment. Digested solids can be stacked and are stable; they will not undergo further anaerobic decomposition during storage. The stabilized solids are easier to handle and transport than raw manure, decreasing the amount of time and money spent on those processes. Additionally, the digested solids are ideal feedstock for composting systems—the digested manure solids heat faster than raw solids, improving the composting process.

Depending on the temperatures reached during digestion, **pathogen** reductions of up to 90 percent are possible (Frame et al., 2001). When appropriate temperatures are reached, **fecal coliform** counts are reduced 99 percent (Frame et al., 2001). ***E. coli*** and ***Salmonella*** may be killed, as may fly eggs and weed seeds, by the heat produced during digestion, decreasing farm **vector** potential.

The methane produced by the anaerobic microorganisms may be used in the same way as **natural gas** or **LP gas.** The power generated may be used directly on the farm or sold back to the power utility. Power sold to the utility can help recover a portion of the installation and operation costs over time. Biogas-driven engines produce waste heat—this heat can be used to produce hot water or heat on the farm.

Pathogen: A disease-causing organism.

Fecal coliform: A group of bacteria in the family Enterobacteriacea and commonly found in the digestive tracts of all mammals. The presence of fecal coliform in water may indicate fecal contamination and the existence of pathogens.

E. coli: *Escherichia coli;* a type of bacteria found in the digestive tracts of all mammals that may be used as an indicator organism to determine if pathogens are present. *E. coli* OH:157 is a pathogenic strain of the bacteria.

Salmonella: A bacteria found in the digestive tracts of animals that can cause food poisoning in humans.

Vector: An agent that transfers a disease or pathogen from one organism to another.

Natural gas: A naturally occurring mixture of hydrocarbons, principally methane, and non-hydrocarbons; found in porous geological formations, often in association with crude oil. Natural gas is the cleanest burning fossil fuel.

LP gas: Liquefied petroleum gas; a family of light hydrocarbons called "gas liquids" comprised mostly of propane (C_3H_8) and butane (C_4H_{10}). LP gas is derived from natural gas processing and crude oil refining and can liquefy under modest pressure and cooling for easy storage and transportation.

Flare: A method of burning biogas to prevent explosive gases from accumulating or entering the atmosphere.

Acidogenesis: The formation of propionic and butyric acids from glucose.

5.2.2 Disadvantages

Anaerobic digestion is not without drawbacks. Implementing an anaerobic digester requires a substantial amount of planning, resources, and commitment by the farm operator. Anaerobic digestion is an engineered system that is typically more complex and more costly to construct than other manure treatment processes. These treatment processes can be difficult to operate and maintain. Nitrogen and phosphorus levels are not affected by anaerobic digestion.

While the solids content of anaerobically digested manure is reduced, the total volume of manure is not reduced appreciably. Manure is primarily water with about 90 to 95 percent moisture content (Frame et al., 2001).

One potential water quality disadvantage of anaerobic digestion is that it does not reduce nutrient levels. While digestion concentrates the nutrients into a smaller solids volume, the total nutrient levels are not reduced. The nutrient pollution potential as well as the fertilizer value of the solids is neither enhanced nor diminished by anaerobic digestion.

Odors are normally controlled with anaerobic digestion but some odors may be released during digester cleaning and maintenance. Ammonia, an air pollutant, may be emitted from some anaerobic digesters. Since ammonia is an air pollutant, it may be necessary to add air strippers to the digester for ammonia treatment.

Antibiotics in the manure and detergents, acids, and halogens used in equipment cleaning and maintenance may negatively affect bacterial action. Some anaerobic digesters will not operate at temperatures high enough to effectively eliminate pathogens. Frozen manure should never be added to an anaerobic digester, and the digester may require heating during cold weather.

Even though methane generation can produce energy, it may not provide the economic incentive that it does elsewhere in the world. Small farms may not benefit financially from a digester. Anaerobic digestion requires consistently high temperatures and the power generated during cold periods may only be enough to keep the digester minimally heated. Since seasonal temperature variations affect biogas production, it is not generally possible to rely solely on the production to meet 100 percent of the farm's energy needs especially since energy for barn ventilation must be provided at all times. While excess energy may be sold back to the utility company, it may take a long time to recover the complete cost of the digester. All anaerobic digesters should be equipped with a **flare**, as biogas is highly flammable.

5.3 Anaerobic Process

Anaerobic digestion is a process involving different populations of anaerobic bacteria. Each population performs specific tasks that are important to the overall digestion process.

Anaerobic digestion occurs in three steps, as illustrated by **figure 5.1**:

1. Liquefaction,
2. **Acidogenesis,** and
3. Methanogenesis.

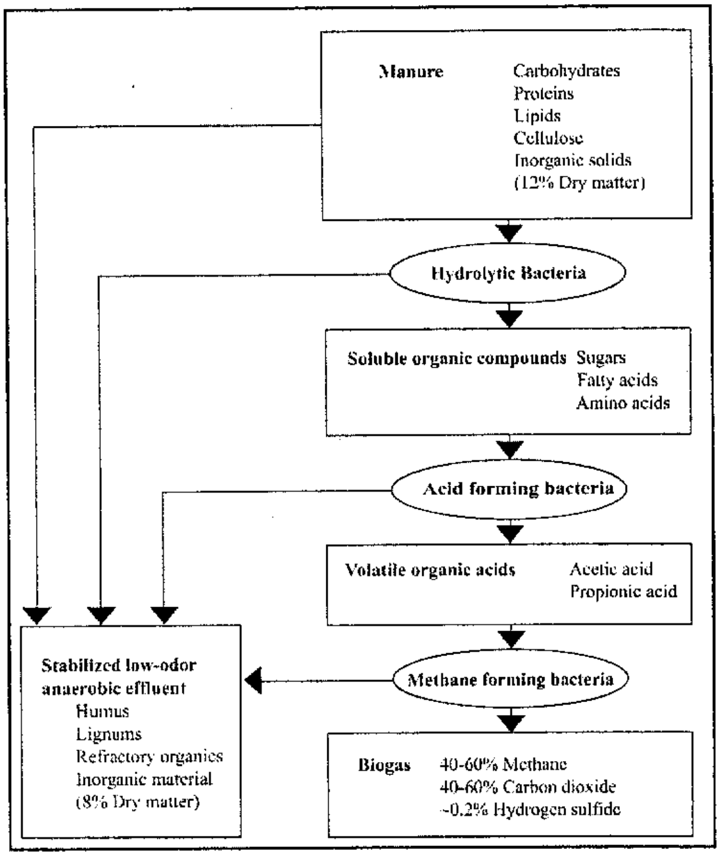

Figure 5.1: Anaerobic digestion process chart (adapted from P. Wright, 2001).

5.3.1 Liquefaction

Liquefaction is a rapid process. In liquefaction, bacteria convert complex organic materials such as proteins, fats, and carbohydrates into soluble forms. The liquefying bacteria break down the complex organic materials by **hydrolysis.**

5.3.2 Acidogenesis

Acidogenesis is sometimes broken into two individual processes—acidogenesis and **acetogenesis**. Two kinds of bacteria are active in this step, fermentative and acidogenic bacteria. These bacteria together convert the soluble carbohydrates, fats, and proteins to simple, short-chained organic acids. These organic acids are food for the methanogenic bacteria.

5.3.3 Methanogenesis

The final step of anaerobic digestion is methanogenesis, also known as gasification. **Methanogens** consume the short-chained acids and produce biogas.

Methanogens are the limiting biological factor in anaerobic digestion. These methane-producing bacteria need a steady supply of simple acids in order to live and reproduce. The manure loading rate to the digester must be steady in order to feed these finicky bugs. It generally takes 20 to 25 days for methanogens to grow and reproduce to replace the bacteria lost when digested manure is removed from the reactor (Wright, 2001). Shorter times are possible when conditions are completely optimal and a growth media is available to which the bacteria can cling. Methanogens are extremely sensitive to pH. A pH of 6.0 to 8.0 is required, with 7.0 as an optimal level (Wright, 2001). Methanogens can operate in three temperature regimes:

1. Psychrophilic,
2. Mesophilic, and
3. Thermophilic.

Psychrophilic temperatures are less than 20° C (68° F) (Wright, 2001). The methanogens grow and reproduce most slowly at this temperature. This temperature requires longer treatment times and does not generally produce enough biogas to warrant the expense

Hydrolysis: The decomposition of a compound by reaction with water.

Acetogenesis: The formation of acetic acid from carbon dioxide and hydrogen.

Methanogens: Bacteria that produce methane gas by combining acetic acid, hydrogen gas, and carbon dioxide.

Helminth: An intestinal parasitic worm.

Lagoon: A shallow pond where sunlight, oxygen, and bacteria degrade and transform compounds in manure.

Tipping fees: The fees earned for the collection of unwanted materials.

of biogas collection and utilization equipment. This is the temperature that most digesters located in cold climates operate at for most of the year.

The mesophilic regime operates from about 20° C (68° F) to 37.8° C (100° F) (Wright, 2001). This is the most common temperature range for an anaerobic digester operation. Mesophilic digesters are more reliable than their warmer thermophilic counterparts, especially in cold weather. Mesophilic temperatures may achieve a 95 percent pathogen-reducing effect (PRE), which destroys the most common pathogens with the exception of some viruses and **helminths**.

The thermophilic temperature regime operates from about 37.8° C (100° F) to 54.4° C (130° F) (Wright, 2001). This temperature range allows for the highest biogas production per unit of time, shortest retention times, and highest level of pathogen reduction. However, it is difficult to achieve and maintain this temperature over long periods.

5.4 Anaerobic Digestion Design Considerations

Anaerobic digestion can take many forms to meet treatment objectives. There are different types of reactor designs but every design considers these five components:

1. Solids separation,
2. Mixing,
3. Digestion,
4. Storage, and
5. Energy conversion.

5.4.1 Solids Separation

Manure containing sand, wood chips, or large amounts of hay should be separated from the digester feedstock. These materials can inhibit the digestion process and damage digester and biogas equipment.

Solids separation is also recommended for highly dilute manure, although some reactor designs such as anaerobic **lagoons** are able to treat more dilute manure. Solids separation should be used with care. Anaerobic bacteria require carbon for growth and reproduction, but separation may remove too much carbon from the digester feedstock. To maintain carbon levels in the digester feedstock, cellulose may be added. Cellulose can improve the conversion of volatile solids to gas. Food waste, milk and food processing waste, and municipal solid waste may provide the needed carbon and may also provide **tipping fees.**

5.4.2 Mixing

A mixing tank is not required, but may improve the consistency and homogeneity of the digester contents, facilitating increased digestion. Mix tanks can also act as temporary storage for untreated manure.

5.4.3 Digestion Reactor

The digestion reactor is the heart of the digestion process. The five key characteristics to consider in designing the actual reactor are:

1. Size,
2. Material,
3. Structural integrity,
4. Heating and insulation, and
5. Manure flow.

a. Size

There are several important parameters used to determine the size of the reactor. The number of animals and amount of **recoverable manure** each animal produces must be determined. The amount of water used for flushing or animal hygiene, waste feed and water, and bedding should be considered. The length of time the manure is treated in the digester is also a factor.

b. Material

Appropriate construction materials are essential. Anaerobic digesters have two distinct environments that the reactor materials need to be compatible with—the area below the manure surface and the area above the manure surface.

Materials located below the surface are in continual contact with the manure. Below the manure surface there is a relatively neutral pH, ranging from 6.5 to 7.5 (Koelsch et al., 1990). The materials must be able to withstand the forces created by the movement of massive amounts of manures as well as the forces that may be exerted on the outside walls of the digester from soil. Digesters are commonly constructed from high quality reinforced concrete. Fiberglass is more resistant to corrosion, but is more expensive. Iron coated with a protective polymer layer can be effective, though costly. Uncoated metals will corrode rapidly in the presence of biogas, and galvanization is not sufficient to prevent corrosion. If the digester is heated, the heat exchanger should be constructed from black iron. All heat exchanger parts should be located below the manure surface to protect them from biogas corrosion.

Above the manure surface the conditions are highly acidic and moist. Biogas is saturated and contains **hydrogen sulfide**, which is extremely corrosive. Materials for this part of the digester should withstand corrosive action and tension from digester covers and gas pipes. Gas pipes above the manure surface can be constructed from black iron. Black iron is sturdy and can be resistant to most mechanical damage that may occur during mixing or loading. However, internal corrosion may occur when in steady contact with wet biogas. Coated steel pipe with plastic lining is an alternative—the lining prevents scale and corrosion. The reactor cover must be gastight to create a completely anaerobic environment. The cover may be constructed from the same material as the wall or from a different material.

c. Structural Integrity

A major concern with anaerobic digesters or any treatment process where manure is concentrated into one location is the possibility for catastrophic failure of the structure. If the reactor is located either partially or fully in-ground and emptied too quickly or if the reactor remains empty for long periods of time the inward pressure provided by the soil may be strong enough to buckle the walls. This hazard is reduced if the reactor is located in a well-drained area, if footer drains are installed, and if the areas around the reactor are back-filled with gravel sloping away from the walls.

Wind and gas pressure may also generate forces on above-ground reactors. Consideration of the prevailing wind direction and strategically placed wind breaks can decrease the pressure and reduce odor issues during reactor cleanout.

Recoverable manure: Manure that can be collected; cow pies deposited in a pasture are non-recoverable.

Hydrogen sulfide: A colorless, flammable, toxic gas (H_2S) that smells like rotten eggs, produced during the decomposition of organic matter.

Aerobic: An oxygenated environment or requiring an oxygenated environment to survive.

Hydraulic retention time (HRT): The amount of time that a substance is retained in a reactor, representing the time required to treat the substance.

d. Insulation and Heating

Anaerobic digesters may be insulated or heated in cool climates for two reasons:

1. To raise the temperature of the incoming manure to 38° C (100° F), and
2. To maintain the temperature of the total manure mass; this is a function of the ambient weather conditions as well as the degree of insulation.

Special care is required in the design of cold-weather anaerobic digesters. Low temperatures will impede digester performance. Frozen manure should never be added to an anaerobic digester. It may be necessary to construct barns or to insulate existing facilities to prevent manure from freezing. Alternatively, manure may be pre-heated before entering a reactor. Both options require additional costs. The degree of insulation and heating needs depend on the climate and type of reactor. If methane production is a treatment goal, a temperature of 37.8° C (100° F) must be maintained even in winter (Koelsch et al., 1990). Insulation is absolutely necessary in this case. All parts of the reactor exposed to the ambient temperature should be insulated.

When insulation is not sufficient enough to maintain an appropriate temperature, a heat exchanger may be required. A heat exchanger is a looped pipe that circulates hot water through the manure. The water heats the pipe and the pipe in turn heats the manure via conduction. The heat exchanger can be embedded in the reactor walls and floor or run throughout the manure mass. Embedded heat exchangers offer a clean design with less obstruction of manure flow. Locating and repairing leaks may be difficult and costly as can the initial construction costs of embedded exchangers. There is also a larger surface area to heat. Exchanger pipes running throughout the manure mass allow for easier maintenance and lower costs than embedded exchangers but the manure flow may be obstructed by the pipes and the manure may cake onto the pipes because of the heat. Black iron is the best material for a heat exchanger; it is strong with a high coefficient of heat transfer. However, black iron is heavy and difficult to work with and must remain completely submerged in manure to prevent corrosion. Plastic has a low coefficient of heat transfer and steel will corrode quickly in the manure; neither material is recommended.

e. Manure Flow

Manure flow is the last major design aspect for anaerobic digesters. The manure inlet to the digester should always be located below the manure surface in the reactor. Placing the inlet below the surface prevents air intrusion and oxygen contamination of the manure, which would convert the anaerobic environment to an **aerobic** environment.

The manure loading rate to the digester is very important. The anaerobic microorganisms require a steady flow of manure for energy production, growth, and reproduction. Regular, frequent loading of manure is preferred—large, irregular feeding may lower the reactor temperature, shocking the bacterial population. The loading rate is a function of **hydraulic retention time (HRT).**

The HRT is dependent on the digester temperature, the manure loading rate, the rate at which digested manure is removed, and the total digester volume. Each of these components is interdependent and these relationships are what make anaerobic digestion design so complicated.

The relationship between the loading rate and the HRT is inverse—as the hydraulic retention time increases, the loading rate decreases. The longer the manure is retained in the digester, the less room there is for new manure to be added. By decreasing the HRT the loading rate can be increased and the digester volume can be decreased, but this will result in a lesser amount of manure converted to biogas.

In addition to the manure loading rate, the design of the digester should minimize **short-circuiting** and solids accumulation.

5.4.4 Storage

The digested manure should be retained in a separate storage facility for further treatment or use. Tanks, pits, and ponds are acceptable storage reservoirs. All storage facilities should be designed to prevent leaking, leaching, overflow, and dilution by precipitation.

5.4.5 Energy Conversion

If biogas production is a treatment objective, the biogas must be collected and purified. For more information on biogas collection and utilization, please see Section 5.6 of this chapter. If biogas production is not a treatment goal, then the biogas must be flared off to prevent a potentially explosive situation. **Figure 5.2** is a photograph of a biogas flare.

5.5 Types of Anaerobic Digester Designs

There are four major kinds of digesters—mixed reactors, fixed film reactors, plug-flow reactors, and lagoons. Most other types of anaerobic digesters are slight variations on these basic designs. Hybrid systems that incorporate two or more digester designs may offer flexibility and more complete digestion.

5.5.1 Mixed Reactors

Mixed reactors blend the manure to produce a homogeneous concoction. This mixing keeps the bacteria in constant contact with the organic matter—their food. Mixed reactors are the smallest of the four digester types, but they tend to be the most expensive digesters. Mixed reactors are a proven treatment technology and are commonly used in municipal wastewater treatment.

Mixed reactors are typically upright tanks that resemble squat tower silos. The squat tower shape has a low profile that blends into the landscape. In Europe, mixed reactors are often egg-shaped, as depicted in **figure 5.3.**

Short-circuiting: Incomplete treatment due to the formation of channels of preferential flow bypassing a portion of the treatment system.

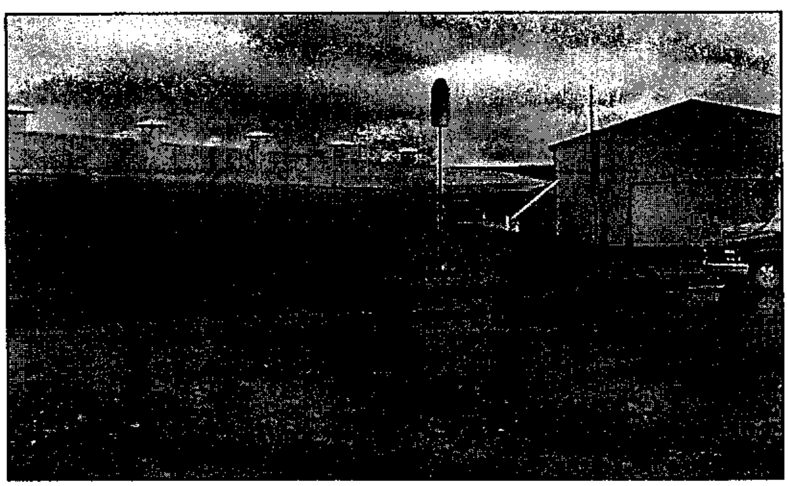

Figure 5.2: Biogas flare (J. Robbins, 2004).

Cogeneration: The simultaneous production of electric energy and thermal energy.

Biomass: The total dry mass of an individual or population.

While the egg-shaped reactors stick out more than squat silos, they enhance mixing and decrease stratification. Mixed reactors can be constructed from a variety of materials.

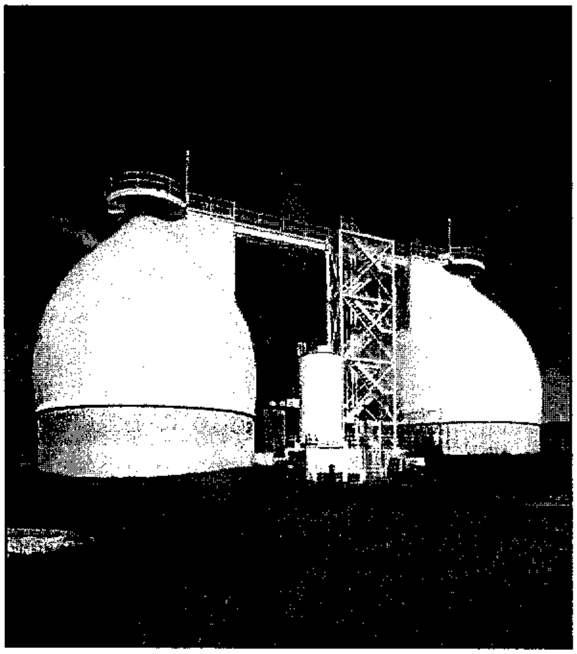

Figure 5.3: Egg-shaped mixed reactor (CBI, 2004).

Mixing is accomplished by thermal convection, mechanical agitation, pumped manure recirculation, or by bubbling compressed biogas through the manure mass. The cost of mixing may be high, especially if floatable materials and silt are present in the manure. However, in terms of the power consumed per unit of volume mixed, mechanical mixers typically are the most efficient (Burke, 2001). The mechanical parts required for mixing increases the maintenance requirements when compared to other digester types with no moving parts.

Manure with solids content of three to ten percent can be digested well in mixed reactors (Moser, 2003). Excess water from flushing or washing will increase the size and cost of the digester. Mixed reactors typically operate on a continuous basis rather than in batches—fresh manure is mixed with manure that has been digested for various lengths of time. Ideal mixing is not possible and some short-circuiting is inevitable. Typical HRTs are 12 days or longer (Moser, 2003).

Mixed reactors can produce a steady volume of gas that can be used in **cogeneration** or in a boiler. Most mixed reactors operate in the mesophilic range, but some may operate in the thermophilic range if heated. Thermophilic reactors will kill a greater percentage of pathogens.

Contact reactors, sequencing batch reactors, temperature-phased reactors, and acid-phased digesters are types of mixed reactor digesters.

a. Contact Reactor

In a contact reactor, the manure passes through an initial digestion stage. It then undergoes a solids separation process to concentrate the bacterial **biomass.** The biomass is cycled back to the digester and mixed with undigested manure. The concentrated bacteria are poised to consume the new manure quickly and efficiently convert more manure solids to gas. Both dilute and concentrated manures may be treated in this manner.

Contact reactors are less likely to fail than other digester designs—the large quantity and diversity of bacteria that is used in the digester process makes the system more robust.

b. Sequencing Batch Reactor

Sequencing batch reactors operate similarly to contact reactors. The digestion and separation typically occur in the same vessel. The reactors operate in fill-and-draw mode—the reactor is filled, the manure is mixed and digested, the mixing is stopped to allow the biomass to settle, and the **supernatant** is drawn off. Two or more reactors are linked in series to achieve a high rate of solid to biogas conversion. **Figure 5.4** is a diagram of a sequencing batch reactor.

c. Temperature-Phased Digestion

Temperature-phased anaerobic digestion is a variation of the mixed reactor design. The digestion occurs in two phases. The first phase takes place at thermophilic temperatures and the second phase occurs in a separate reactor at mesophilic temperatures. The high heat during the thermophilic phase destroys pathogens. Biogas is produced at the mesophilic stage.

Temperature-phased digestion improves odor control, reduces foaming, destroys more volatile solids, improves dewatering characteristics, and increases biogas production. Very dilute manures, such as milking parlor waste, can be treated with this digester type. Temperature-phased digestion is not widely used in manure treatment at this time, but is used in municipal wastewater treatment. Lab and pilot studies with manure have been successful, but there is less field experience with this type of digester.

d. Acid-Phased Digestion

Acid-phased digesters are similar to temperature-phased anaerobic digesters in both the benefits and design. Instead of dividing the process by temperature, this type of digestion divides the process according to the rate of bacterial growth. The first initial reactor is where acidogenesis occurs. The acid-forming bacteria responsible for acidogenesis have a higher growth rate than the bacteria responsible for methanogenesis, which occurs in the second, larger reactor.

Like temperature-phased digestion, acid-phased digestion does not have a long history of field experience with manure treatment and has not been tested extensively with dairy manure.

5.5.2 Fixed Film Reactor

Fixed film reactors contain a medium on which bacteria can cling and grow. This allows the bacteria to be retained in the digester rather than flushed out with the digested manure. A resident population of bacteria forms, reducing

Supernatant: The liquid standing above the layer of solids after settling or treatment.

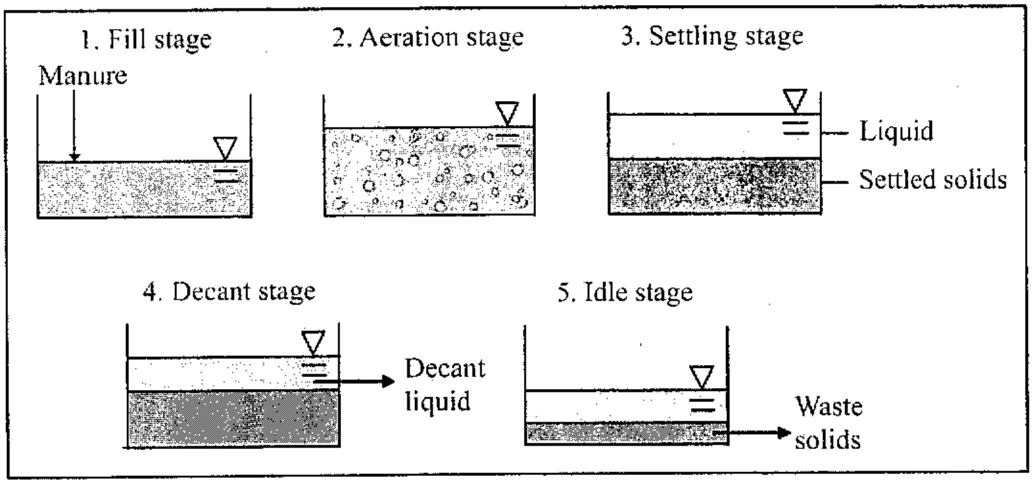

Figure 5.4: Sequencing batch reactor (Metcalf and Eddy, 2003).

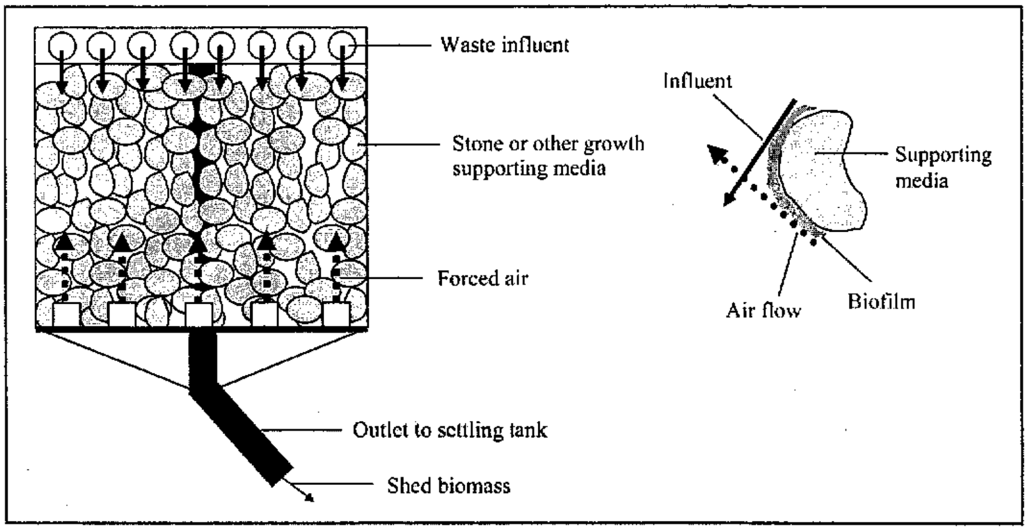

Figure 5.5: Fixed film reactor (adapted from Miner et al., 2000).

the HRT since the time for bacterial growth and reproduction is reduced. Stones, plastic beads, or plastic mesh may be used as the medium. **Figure 5.5** is a diagram of a fixed film digester. Fixed-film digesters cannot tolerate dense inorganic materials and instead work best with relatively dilute manure, such as flushed swine waste.

Typical fixed film HRTs are two to six days (US EPA, 2003). This relatively short retention time allows for a smaller digester volume, which decreases the footprint of the system.

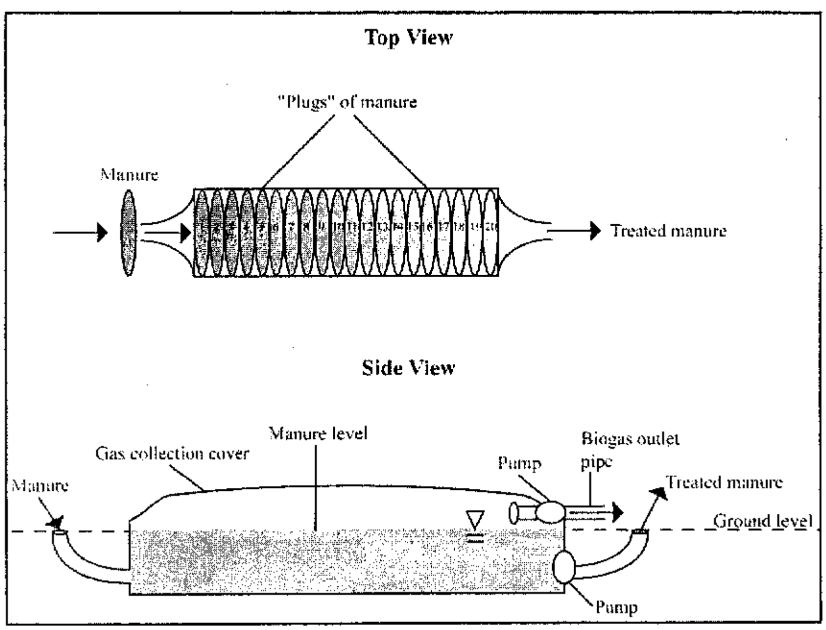

Figure 5.6: Diagram of a plug-flow reactor (J. Robbins, 2003).

5.5.3 Plug-Flow Reactor

Plug-flow reactors are long, narrow, in-ground tanks. In theory, manure moves in "plugs" through the reactor from the inlet to the outlet; the volume of the manure added to the reactor should equal the volume of the digested manure that exits the reactor. **Figure 5.6** is a diagram of a plug-flow anaerobic digester. Plug-flow digesters have relatively little or no short-circuiting, so manure exiting a well-designed reactor should be completely digested. Unlike fixed-film reactors, bacteria are not conserved in plug-flow reactors. A typical HRT for a plug-flow digester is 15 to 20 days (Frame et al., 2001).

Plug-flow digesters can process manure with a solids concentration of 11 to 14 percent (Frame et al., 2001). As-excreted manure is too moist and excess moisture will cause digester malfunction if the solids and liquids were to separate. For this reason, plug-flow reactors are not appropriate for treating swine manure or for milking parlor waste. Bedding materials should be removed from the manure before digestion—bedding tends to float to the manure surface, reducing biogas production. Plug-flow digesters are not able to operate when dense inorganic materials, including sand bedding, are present in the manure.

As with any anaerobic system, plug-flow reactors must be completely air-tight. The cover may be flexible or rigid. **Figure 5.7** is a photograph of a plug-flow reactor.