

Anaerobic Digestion Basics

Lide Chen and Howard Neibling

Introduction

Dairy, potatoes, and sugar beets—all important agricultural commodities in Idaho—also generate a huge amount of wastes. Two big waste-related challenges facing the dairy and food processing industries are emissions of odors and gases and manure management. Gas emissions include greenhouse gases; ammonia (NH_3), a colorless gas with a pungent smell; and hydrogen sulfide (H_2S), a colorless gas with the foul odor of rotten eggs.

Rising energy prices, more restrictive regulatory requirements, and increasing concern over greenhouse gas emissions are causing many people in Idaho's dairy and food-processing industries to consider anaerobic digestion (AD) of wastes from their operations. Anaerobic digestion technology is being viewed as a way to address environmental concerns, generate renewable energy, cut bedding-material costs, reduce

pathogens and weed seeds associated with manure, improve manure nutrient availability to plants, and sometimes generate new revenues.

What Is Anaerobic Digestion?

Anaerobic digestion is a series of biological processes that use a diverse population of bacteria to break down organic materials into biogas, primarily methane, and a combination of solid and liquid effluents, the digestate (figure 1). It occurs in the absence of free oxygen.

Organic materials are composed of organic compounds resulting from the remains or decomposition of previously living organisms such as plants and animals and their waste products. Sources of organic material for anaerobic digestion include dairy manure, food processing waste, plant residues, and other organic wastes such as municipal wastewater, food waste, and fats, oils, and grease.

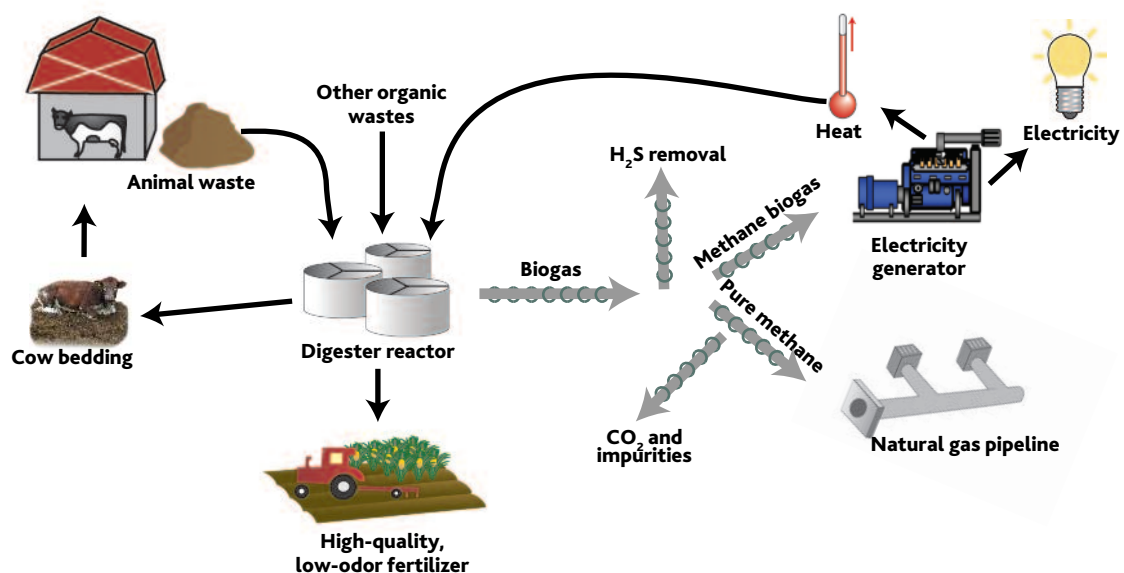


Figure 1. Typical anaerobic digester configurations. (Modified from <https://erams.com/AD-feasibility>. Original prepared by Sarah G. Lupis, Institute for Livestock and the Environment, Colorado State University.)

The end product biogas is composed of methane (CH₄, typically 60–70% by volume) and carbon dioxide (CO₂, typically 30–40% by volume) as well as small amounts of H₂S and other trace gases. Biogas can be combusted to generate electricity and heat or processed into renewable natural gas and transportation fuels.

Separated digested solids can be composted, utilized for dairy bedding, directly applied to croplands, or converted into other products such as potting soil mixes. Digested liquid, which contains fewer pathogens and weed seeds and is rich in crop nutrients, can be used as agricultural fertilizer. Digestion of livestock manure also reduces emissions of greenhouse gases and odors.

Benefits of Anaerobic Digestion

The following benefits are commonly recognized:

- Reducing odor missions, which improves air quality
- Harvesting biogas (mainly the greenhouse gases CH₄ and CO₂), which reduces greenhouse-gas emissions to the atmosphere
- Protecting water quality by reducing the potential for pathogens associated with manure to enter surface and/or groundwater
- Generating energy (gas, electricity, heat) that can be sold for on-farm or off-farm uses
- Killing weed seeds in manure, which reduces costs of controlling weeds in fields
- Reducing bedding costs by using digested fiber
- Improving manure nutrient availability to plants, reducing fertilizer costs
- Possibly receiving carbon credit payments
- Being a better neighbor.

Four-Step Anaerobic Digestion Process

Anaerobic digestion can be divided into four steps (figure 2).

Step 1. Hydrolysis. The first step, hydrolysis, occurs as extracellular enzymes produced by hydrolytic microorganisms (for example, cellulase, amylase, protease, and lipase) decompose complex organic polymers into simple, soluble monomers. Proteins are broken down into amino acids, lipids into long- and short-chain fatty acids, starch into glucose, and carbohydrates into sugars.

Step 2. Acidogenesis. The small molecules resulting

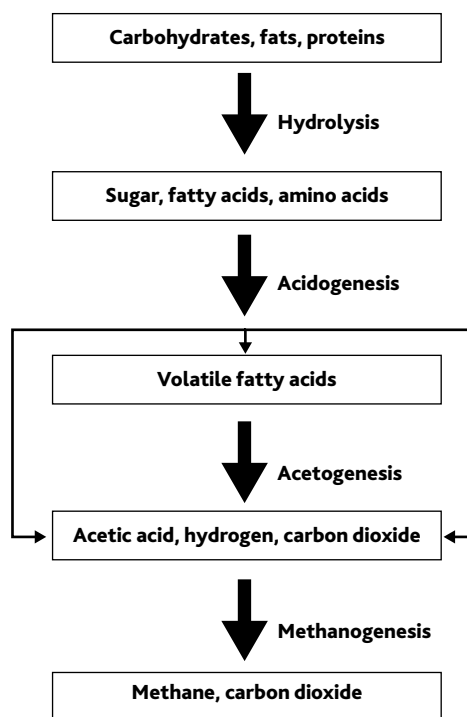


Figure 2. The four-step anaerobic digestion process.

from hydrolysis are converted by acidogens (fermentative bacteria) to a mixture of volatile fatty acids (VFAs) such as acetic, propionic, and butyric acids and other minor products such as hydrogen, carbon dioxide, and acetic acid. Acidogenesis is usually the fastest step in the anaerobic conversion of complex organic matter in liquid-phase digestion.

Step 3. Acetogenesis. In the third step, acetogenic bacteria further convert the volatile fatty acids to acetate, CO₂, and/or hydrogen (H₂).

Step 4. Methanogenesis. Step 3 provides substrates for methanogenesis, the last step in the anaerobic process for methane production.

A stable anaerobic digestion process requires maintaining a balance between several microbial populations. The hydrolysis and acidogenesis steps have the most robust microbes (acid formers), which thrive in the broadest environmental range. They react quickly to increased food availability, so the fatty acid concentration could rise very quickly. The pH range is maintained under normal circumstances by the buffering action of the system provided by CO₂ in the form of bicarbonate (HCO₃⁻) alkalinity. However, if the acid concentration overcomes the system's buffering capacity, the pH value could be out of the acceptable limits of the acetogenic and methanogenic bacteria (methane formers). When this happens, methane production stops and the acid levels rise to the tolerance level of the acid formers, thus resulting in system failure.

In addition to pH, temperature is a critical factor affecting the balance between these microbial populations. Sudden changes in temperature adversely affect the methane formers, thus affecting the acid formers, too. Any change having an adverse effect on the methane formers increases acid concentration, which in turn reduces the activities of the methane formers.

Feedstocks

Livestock manure and many other substrates including food processing wastes such as cheese whey, yogurt factory wastewater, sugar beet processing wastewater, and fruit and vegetable wastes are commonly used feedstocks.

Feedstock characteristics are important factors affecting biogas production and process stability during anaerobic digestion. The main characteristics of feedstocks include moisture content, total solids (TS), volatile solids (VS) (organic compounds of plant or animal origin that are lost on ignition of the dry solids at 550 °C [1022°F]), particle size, pH, biodegradability, chemical oxygen demand (COD), biological oxygen demand (BOD), and carbon and nitrogen contents. The concentration of volatile fatty acids and NH₃, both of which could cause toxicity and process failure at high concentrations, is largely dependent on feedstock characteristics and loading rates.

Table 1 shows the characteristics of lactating dairy cow manure and its biogas potential.

Table 1. Characteristics of lactating dairy cow manure and its biogas potential.

Component	Units	Per cow
Weight	lb/day	150.00
Volume	cubic feet/day	2.40
Moisture	percent	87.00
Total solids	lb/day	20.00
Total volatile solids	lb/day	17.00
Chemical oxygen demand (COD)	lb/day	18.00
Biological oxygen demand (BOD)	lb/day	2.90
Nitrogen	lb/day	0.99
Phosphorous	lb/day	0.17
Potassium	lb/day	0.23
Biogas production ^a	cubic feet/day	47.10
Methane production ^b	cubic feet/day	30.60
Methane (CH ₄) ^b	lb/day	1.37
kWh ^c	per day	2.00
Annual kWh		744.00

Source: Liebrand, C. B., and Ling, K. C. 2009. Cooperative approaches for implementation. USDA Rural Development Research Report 217. of dairy manure digesters. <http://www.rurdev.usda.gov/supportdocuments/RR217.pdf> (accessed November 18, 2013)

^a90% of the manure collected; 30% conversion rate of COD to methane

^bBiogas with 65% methane

^c366.6 kWh per 1,000 cubic feet methane

Important Operating Factors Affecting Anaerobic Digestion

Temperature

Two distinct temperature ranges are most suitable for biogas production, and different bacteria operate in each of these ranges. Mesophilic bacteria optimally function in the 90°F to 110°F range. Thermophilic bacteria are most productive in the 120°F to 140°F range. Thermophilic digestion kills more pathogenic bacteria, but the cost to maintain a higher operating temperature is greater. Thermophilic digesters may also be less stable.

Bacterial digestion in covered lagoons at temperatures below 90°F is called psychrophilic. Psychrophilic means a preference for lower temperatures; however, digestion slows down or stops completely below 60°F or 70°F, so these digesters do not produce methane all of the time.

Temperature within the digester is critical, with maximum conversion occurring at approximately 95°F in conventional mesophilic digesters. For each 20°F decrease in temperature, gas production falls by approximately 50%. Even more significant is the need to keep the temperature steady since the methane formers are temperature sensitive.

Hydraulic retention time and loading rate

Hydraulic retention time (HRT), the average time that a given volume of sludge stays in the digester, is one of the most important design parameters affecting the economics of a digester. For a given volume of sludge, a smaller digester (lower capital cost) results in a shorter HRT. This may not be long enough to reach the optimum result such as higher biogas production, lower emissions of odor and greenhouse gases, and higher destruction of chemical oxygen demand, total solids, volatile solids, pathogens, and weed seeds. A HRT range of a few to 40 days is recommended depending on digester type and solids content in feedstocks (table 2).

Table 2. Recommended waste solids content for anaerobic digesters.

Digester type	Solids content (%)	Typical hydraulic retention time (days)	Temperature
Covered lagoon	N/A	30–40	Psychrophilic
Plug flow	11–14	10–25	Mesophilic (68–113°F, optimally around 86–100°F) or thermophilic (122–131°F up to 158°F)
Complete mix	5–10	10–25	Mesophilic or thermophilic
Fixed film	<1	A few days	Mesophilic or thermophilic

Source: www.engr.colostate.edu

Loading rate is the amount of volatile solids fed daily to the digester. Experience indicates that uniform loading, on a daily basis, of feedstocks generally works better.

Co-anaerobic digestion

Animal manure is used as a sole feedstock for most of the digesters currently operating around the world to produce biogas. Although convenient and feasible, using animal manure alone may not represent the most efficient way to produce biogas due to manure's inherent deficiency of carbon (i.e., low carbon/nitrogen ratio if excessive amounts of exposed feedlot manure are in the input stream). Amending dairy manure with other types of organic waste (co-anaerobic digestion) could improve the carbon to nitrogen ratio and biogas production, making the economics of these digesters more favorable.

Anaerobic digestion of more than one substrate in the same digester could establish positive synergisms. The added nutrients could support more microbial growth. During mesophilic co-anaerobic digestion (co-AD) of cattle manure plus fruit and vegetable waste in a continuous stirred tank reactor at 95°F, methane production increased from 230 to 450 ml g⁻¹ VS when the fruit/vegetable waste increased from 20% to 50%. Another co-AD of cow manure and organic fractions of municipal solid waste at 131°F with HRTs of 14 to 18 days indicated that adding such waste to the manure significantly increased the methane yield: from 200 ml g⁻¹ VS for manure alone to 340 ml g⁻¹ VS for the mixture (50% each based on VS).

pH

It should be kept in a range of 6.5 to 7.5. The methane formers are pH sensitive, and pH values outside of the range will affect their metabolic rates and slow or completely stop methane production, resulting in decreased biogas production or digester failure.

Pretreatment

Lignocellulosic biomass, such as agricultural residuals and energy crops (for example, switch grass and Miscanthus), consist mainly of cellulose, hemicelluloses, and lignin. These three compounds render lignocellulosic biomass resistant to biodegradation. Therefore, physical, chemical, or biological pretreatments are preferred.

Safety

Methane (the major component of the biogas generated from anaerobic digestion), when mixed with air, is highly explosive. In addition, biogas is heavier than air, and it displaces oxygen near the ground if it leaks from a digester and accumulates in a nonventilated space. Further, biogas can act as a deadly poison if H₂S is present, which occurs most commonly in the biogas from anaerobic digestion of manure. Given these three points, extreme caution is warranted when operating an anaerobic digester.

Types of Anaerobic Digesters for Animal Farms

Covered lagoons

A covered lagoon digester is a large, in-ground, earthen or lined lagoon with a flexible or floating, gas-tight cover (figures 3 and 4). Covered lagoons are used for digester feedstock of 0.5 to 2% solids. They are not heated digesters. Hydraulic retention time is usually 30 to 45 days or longer. They are best used in warmer regions, where atmospheric heat can help maintain digester temperature.

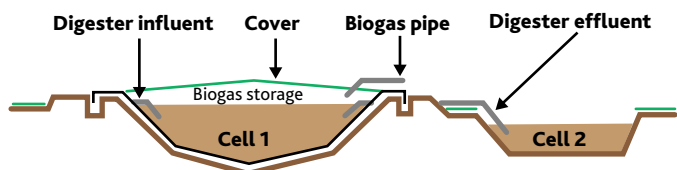


Figure 3. Covered-lagoon schematic. (Source: <http://www.epa.gov/agstar/anaerobic/ad101/anaerobic-digesters.html>)



Figure 4. Covered-lagoon digester. (Source: <http://www.epa.gov/agstar/anaerobic/ad101/anaerobic-digesters.html>)

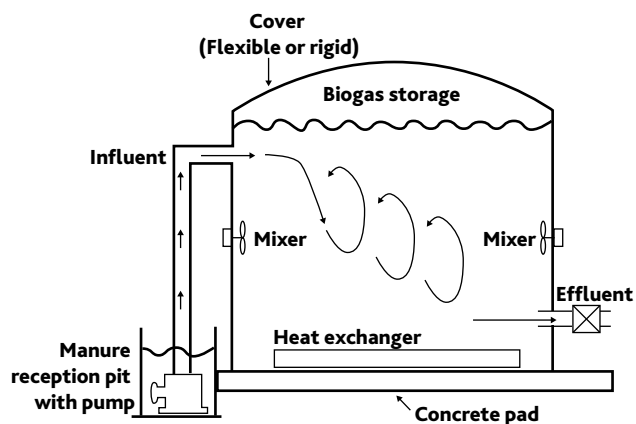


Figure 5. Complete-mix digester schematic (Source: <http://www.epa.gov/agstar/anaerobic/ad101/anaerobic-digesters.html>)



Figure 6. Complete-mix digester. (Courtesy of Leo Maney, Clear Horizons LLC).

Complete-mix digesters

Complete-mix digesters are either aboveground cylindrical tanks or belowground rectangular pits where manure is mixed (figures 5 and 6). They have either rigid or flexible covers. The operating temperature can be in either the mesophilic or thermophilic range. The complete-mix digester is best suited to process manure with 3 to 10 % solids. HRT ranges from 10 to 25 days.

Plug-flow digesters

A plug-flow digester consists of a cylindrical tank in which the gas and other by-products are pushed out one end by new manure being fed into the other end (figure 7). This design handles feedstock consisting of 11 to 14% solids and typically employs hot-water piping through the tank to maintain the necessary temperature. The plug-flow system accounts for more than 50% of all digesters presently in use in the United States.

A plug-flow digester consists of a long, narrow, insulated and heated tank, which is built partially or

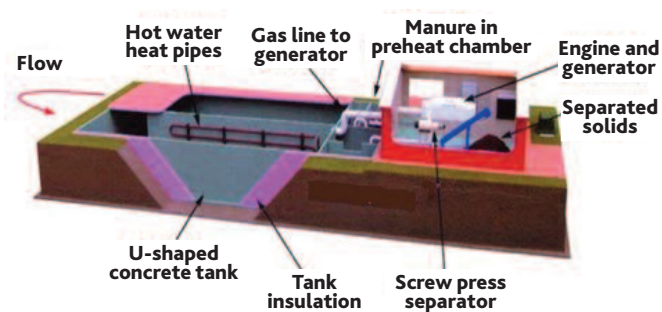


Figure 7. Plug-flow digester schematic. (Source: Jerry Bingold, Innovation Center for U.S. Dairy).

fully below the ground, with a rigid or flexible cover. It is usually operated in the mesophilic temperature range. It is most appropriate for livestock operations that remove manure mechanically rather than wash it out. Manure is added each day at one end of the digester and is decomposed as it moves through the system as a “plug.” After a 15- to 30-day HRT, the plug of manure will reach the outlet of the digester.

Fixed-film digester

A fixed-film digester is essentially a column packed with media, such as wood chips or small plastic rings, that supports a thin film of bacteria called a biofilm (figures 8 and 9). Methane-forming microorganisms grow on the media.

This design handles feedstock containing 1 to 2% solids and uses a shorter retention time, as short as 2 to 6 days. The short HRT allows the use of relatively small digesters compared with other digester options for a given volume of influent. Usually, effluent containing less than 1% solids is recycled to maintain a constant upward flow.

One drawback to fixed-film digesters is that manure solids can plug the media. Removing manure solids from these digesters reduces potential biogas production.

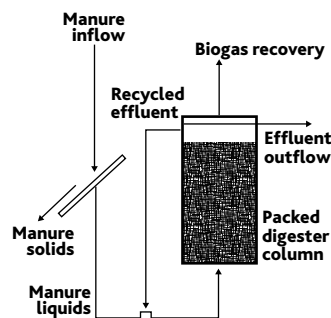


Figure 8. Fixed-film digester schematic. (Source: <http://www.extension.org/pages/30307/types-of-anaerobic-digesters>).



Figure 9. Fixed-film digester. (Courtesy of Ann Wilkie, University of Florida—IFAS).

Anaerobic Digestion Technology Selection

Different types of anaerobic digesters may be appropriate for a specific animal farm depending on its manure-handling methods. Selection of anaerobic digester type is also highly dependent on solids content (table 2).

A number of hybrid systems are being designed and installed. This is a strong indication that no single system is right for all situations. For Idaho dairies, the plug-flow and complete-mix digesters appear to be suitable types.

About the Authors:

Lide Chen, Extension Waste Management Engineer, University of Idaho Twin Falls Research and Extension Center; **Howard Neibling**, Extension Water Management Engineer, University of Idaho Kimberly Research and Extension Center

Additional Resources

Publications

- Balsam, J. 2006. Anaerobic Digestion of Animal Wastes: Factors to Consider. National Center for Appropriate Technology. Available on the Web at: <https://attra.ncat.org/attra-pub/summaries/summary.php?pub=307>
- Barker, J. C. 2001. Methane Fuel Gas from Livestock Wastes: A Summary. Publication #EBAE 071-80. North Carolina State University Cooperative Extension Service, Raleigh, NC.
- Callaghan, F. J., Wase, D. A. J., Thayani, K., and Forster, C. F. 2002. Continuous Co-digestion of Cattle Slurry with Fruit and Vegetable Wastes and Chicken Manure. *Biomass Bioenergy* 27(1): 71–77.
- Hartmann, H., and Ahring, B K. 2005. Anaerobic Digestion of the Organic Fraction of Municipal Solid Waste: Influence of Co-digestion with Manure. *Water Res.* 39(8): 1543-1552.

Websites

- United States Environmental Protection Agency (<http://www.epa.gov/agstar/anaerobic/>)
- eXtension (<http://www.extension.org/pages/30307/types-of-anaerobic-digesters>)
- Penn State Extension (<http://extension.psu.edu/natural-resources/energy/waste-to-energy/resources/biogas>)
- Cornell University (http://www.manuremanagement.cornell.edu/Pages/Topics/Anaerobic_Digestion.html)
- Colorado State University (<http://www.engr.colostate.edu/~jlabadie/Decision%20Tree/intro.cfm>)

Issued in furtherance of cooperative extension work in agriculture and home economics, Acts of May 8 and June 30, 1914, in cooperation with the U.S. Department of Agriculture, Charlotte V. Eberlein, Director of University of Idaho Extension, University of Idaho, Moscow, Idaho 83844. The University of Idaho provides equal opportunity in education and employment on the basis of race, color, national origin, religion, sex, sexual orientation, age, disability, or status as a disabled veteran or Vietnam-era veteran, as required by state and federal laws.