EPA/600/R-15/304 | October 2015 | www.epa.gov/research

United States
Environmental Protection
Agency

Anaerobic Digestion and its Applications





Office of Research and Development
NRMRL/LRPCD

EPA/600/R-15/304
October 2015

Anaerobic Digestion and its Applications

by

Allison Costa, USEPA, AgSTAR, OAR
Charlotte Ely, USEPA, Region 9
Melissa Pennington, USEPA, Region 3
Steve Rock, USEPA, NRMRL, ORD
Carol Staniec, USEPA, Region 5
Jason Turgeon, USEPA, Region 1

Land Remediation and Pollution Control Division
National Risk Management Research Laboratory
Cincinnati, OH 45268

Abstract

On September 16, 2015, U.S. EPA Administrator Gina McCarthy and U.S. Department of Agriculture Secretary Tom Vilsack announced the United States' first-ever national food waste reduction goal, calling for a 50-percent reduction by 2030. The U.S. Environmental Protection Agency (U.S. EPA) seeks to prevent and reduce wasted food (and other organic materials) that will otherwise be lost as a resource into landfills. "Let's feed people, not landfills. By reducing wasted food in landfills, we cut harmful methane emissions that fuel climate change, conserve our natural resources, and protect our planet for future generations" said EPA Administrator Gina McCarthy. "Today's announcement presents a major environmental, social and public health opportunity for the U.S., and we're proud to be part of a national effort to reduce the food that goes into landfills."

This paper provides a brief overview of the science of anaerobic digestion (AD). It describes how increased implementation of AD systems supports current EPA priorities and summarizes current applications of AD systems to achieve various environmental goals. Information is presented on the connection between AD systems and EPA's strategic goals and cross-agency strategies.

The phrase anaerobic digestion refers to both a natural process and an engineered technology. There are many configurations and combinations of parts that can be called an AD system. The technology can be and is used for a range of goals. A discussion of the components, possible products, and multiple uses of the various technologies is included.

Concepts and nomenclature are introduced to show the range of AD system applications and describe the uses of AD products. Regulations are discussed but the document is not intended as a handbook or a regulatory guide. The authors envision that the paper will serve as a framework for continued discussions on how the use of AD systems can achieve EPA's strategic and programmatic goals.

Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) within the Office of Research and Development (ORD) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

Cynthia Sonich-Mullin, Director
NRMRL, ORD

Table of Contents

Abstract	iii
Foreword	iv
Acknowledgments	vi
Executive Summary	1
Scientific Overview	4
EPA's Interest in AD	5
Applications of AD	7
Current AD facilities in the US	12
References	13
Appendix	14
Glossary	17

Figures

Figure 1. Anaerobic Digestion System Components	3
Figure 2. The Chemical Reactions that occur during Anaerobic Digestion	4

Acknowledgments

This paper was conceived, written, reviewed, and edited by EPA staff. The authors would like to acknowledge the many people who contributed to this work and the careful reviewers. Many Offices and Regions contributed time and energy to make this wide collaboration successful.

In particular the reviews of Phil Zahreddine (Office of Water (OW)), Linda Barr (Office of Solid Waste and Emergency Response (OSWER)), Lana Suarez (OSWER), Virginia Till (Region 8), and Pamela Franklin (Office of Air and Radiation (OAR)) were helpful. Bob Bastian (OW), Bill Dunbar (Region 10), and Jay Bassett (Region 4) contributed extensive useful comments as well.

All photos included were taken by the authors.

Executive Summary

Prior to January 2014, there were a number of EPA technical staff working individually on various aspects of anaerobic digestion (AD) projects in the Regions, Office of Solid Waste and Emergency Response (OSWER), Office of Air and Radiation (OAR), Office of Research and Development (ORD) and Office of Water (OW). As AD applications become more widespread and visible, the Agency began receiving an increase in the number of internal and external inquiries surrounding AD systems.

As EPA integrates sustainability concepts into long and short term waste and wastewater management frameworks, AD continues to be identified as a useful tool. As the individual offices continued working with AD applications within their media structure, different frames of reference regarding the benefits of AD processes emerged.

Some of the benefits from effective use of AD systems can include:

- nutrient management alternatives;
- soil improvement opportunities;
- methane emissions reduction;
- production of renewable energy; and
- diversion of organic wastes from less preferred disposal options.

AD systems are built by stakeholders for different reasons, including a waste treatment step, a means to reduce odors, a source of additional revenues or a way to improve public image. The individuals working with AD systems in their respective media(s) became increasingly aware that AD systems are one of many tools that can support the environmental goals and strategies of several different EPA offices. It also became apparent that the Agency would benefit from an OneEPA approach to capitalizing on the different media approaches and benefits that AD systems can offer.

In February 2014, a true Cross-Agency AD Team made up of individuals from different EPA offices and Regions was formed. There are approximately 60 people on this team. The Cross-Agency AD Team's purpose is to share information so members gain a better understanding of the differing perspectives throughout EPA regarding AD systems. The Cross-Agency AD Team strives to communicate effectively and therefore avoid working at cross purposes.

Soon thereafter, in March 2014 a smaller group of individuals was formed to focus on the technical aspects of AD and its applications. This team, the Core AD Technical Team, or Core Team, is composed of technical individuals from EPA offices and regions that are working on AD applications and systems. The mission of the Core Team is to

synthesize the Agency's knowledge, reach consensus regarding technical and scientific facts surrounding AD systems, and develop consistent and effective communications about anaerobic digestion. This Core Team also solidifies effective communication across EPA Regions, OSWER, OAR, OW and ORD.

Core AD Technical Team Members (in alphabetical order):

Jay Bassett, Region 4
Bob Bastian, OW
Allison Costa, AgSTAR, OAR
Bill Dunbar, Region 10
Charlotte Ely, Region 9
Amanda Hong, Region 9
Melissa Pennington, Region 3
Steve Rock, NRMRL, ORD
Carol Staniec, Region 5
Jason Turgeon, Region 1



Intent of the Authors:

This paper is the first of many collaborative efforts of the Core AD Technical Team. The mission of the Core Team is to synthesize the Agency's knowledge, reach consensus regarding technical and scientific facts surrounding AD and develop consistent and effective mechanisms for messaging about anaerobic digestion. This document was peer reviewed by representatives of OSWER, OAR and OW in accordance with ORD's peer review protocol.

This document will help us achieve the mission of the Core AD Team by:

1. Presenting basic technical information and indisputable facts regarding the anaerobic digestion process to anyone interested in learning about the technology.

2. Describing the facts regarding the ability of AD systems to achieve OneEPA goals as well as regional initiatives i.e., the Great Waters Program.

3. Communicating information on AD systems as OneEPA.

4. Capturing the perspectives of and emphasizing agreement reached by all three media offices (OSWER, OW and OAR) and the EPA Regions.

5. Clarifying the definition of terms associated with AD and AD systems to promote consistent language and messaging generated by EPA.

6. Highlighting how the use of AD systems to meet program goals aligns with EPA's FY2014-2018 Strategic Plan and Cross-agency Strategies.

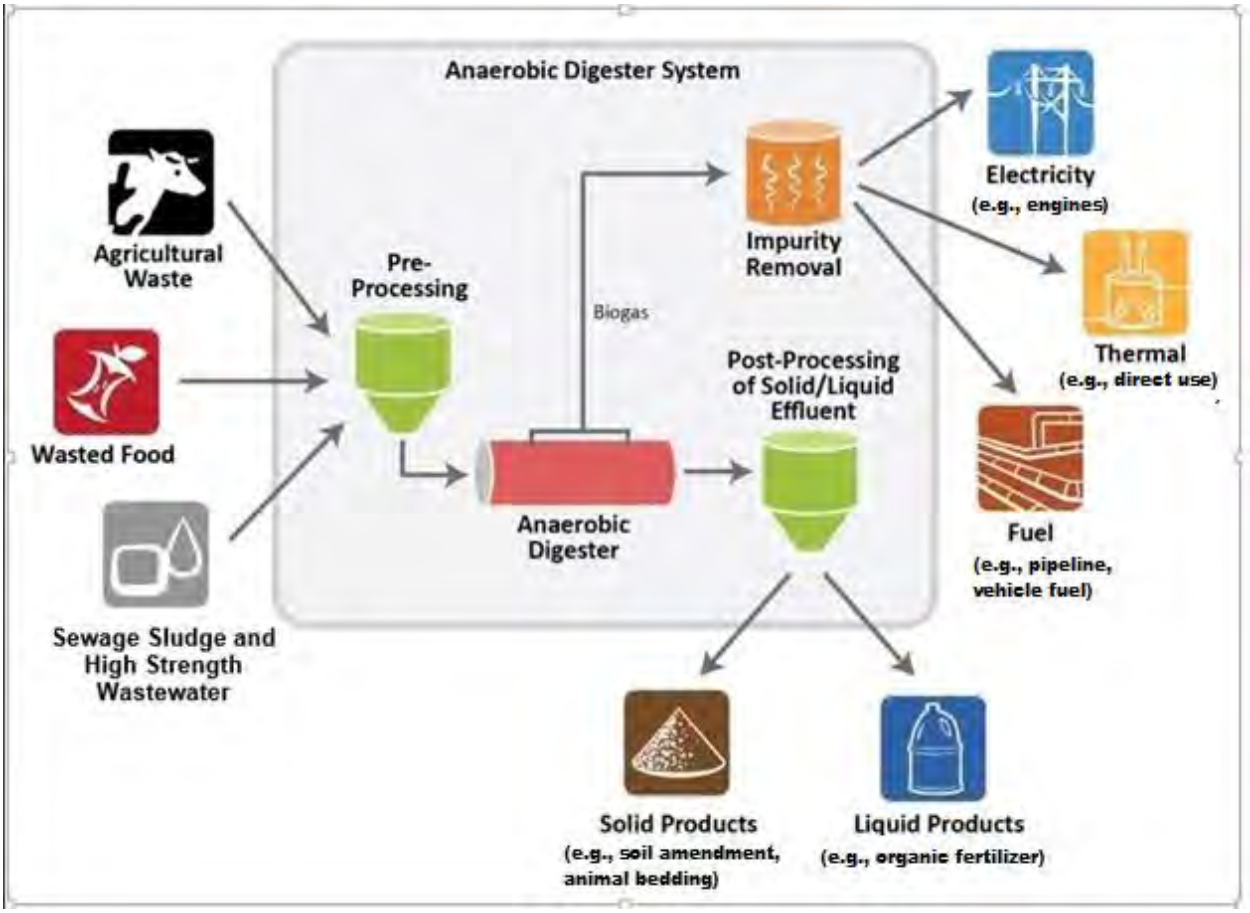


Figure 1. Anaerobic System Components

Scientific Overview

Anaerobic digestion is a natural biological process. The initials “AD” may refer to the process of anaerobic digestion, or the built systems of anaerobic digesters. While there are many kinds of digesters, the biology is basically the same for all. Anaerobic digesters are built systems that deliberately harness the natural process. AD systems can minimize odors and vector attraction, reduce pathogens, produce gas, produce liquid and solid digestate, and reduce waste volumes.

Anaerobically digesting organic carbon involves naturally occurring bacteria. Digestion takes place when organic materials decompose in an oxygen-free environment. Some digester systems differentiate between “wet” and “dry” digesters, or low-solid and high-solid systems, and sometimes the process is called fermentation. The different language used to describe the same processes reflect the varied historical uses and development of AD.

During digestion, various microbes use the organic matter such as animal manure, sewage sludge, wasted food and other organics in the absence of oxygen. The process can be controlled and enhanced through chemistry and engineering.

The chemical reactions that occur in stages during anaerobic digestion are hydrolysis, fermentation, also called acidogenesis (the formation of soluble organic compounds and short-chain organic acids), and methanogenesis (the bacterial conversion of organic acids into methane and carbon dioxide) (Metcalf & Eddy, 2003).

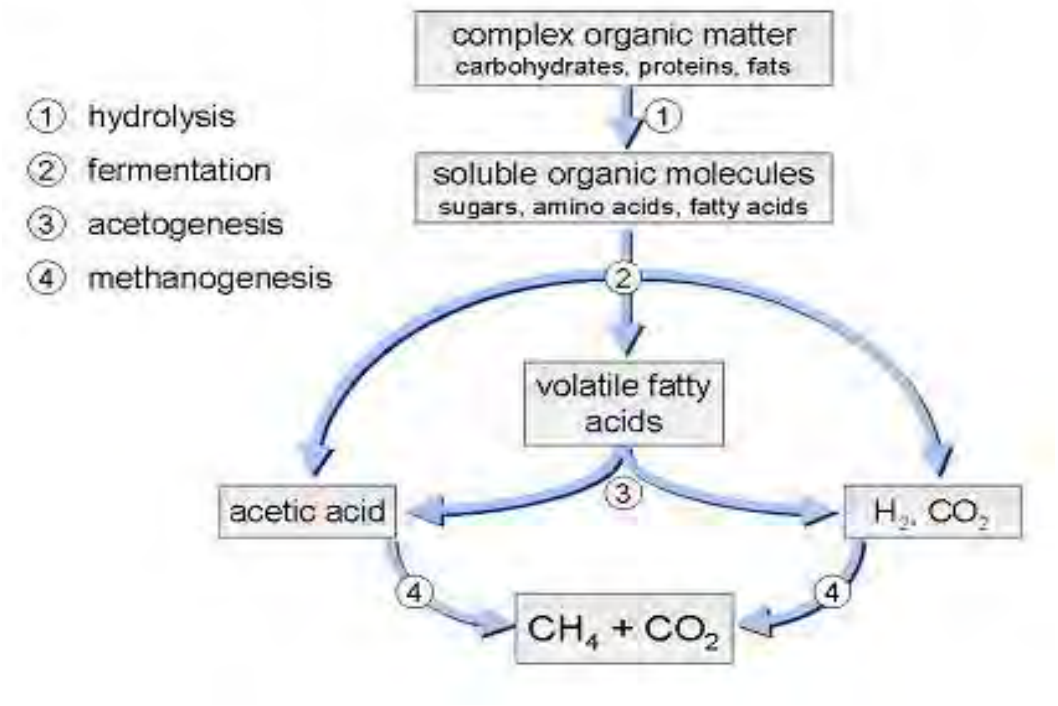


Figure 2. The chemical reactions that occur during anaerobic digestion

In the methanogenesis step, acetic acid, carbon dioxide, and hydrogen are converted to biogas by methanogens. Biogas consists mainly of methane and carbon dioxide and can be used as a renewable energy fuel in a variety of applications.



EPA's Interest in AD

AD systems are installed by stakeholders for many different purposes, such as a waste treatment step, a means to reduce odors, a source of additional revenues, or a way to improve public image.

AD systems can impact several environmental sectors, particularly methane control, production of renewable energy, and integrated waste management. This illustrates EPA's views on AD in relation to its crosscutting strategies to achieve Agency priorities in Air, Water, Waste, and Climate Change:

Biogas production was recognized as a key component of the President's Climate Action Plan: The USDA (along with EPA and DOE) was tasked with developing a Biogas Road Map as part of the directives in the President's Climate Action Plan: Strategy to Reduce Methane Emissions (Climate Action Plan).

AD can help EPA support the following strategic goals:

A) Taking action on climate change: AD projects can minimize the threats posed by climate change in a number of significant ways:

   AD projects reduce greenhouse gas emissions by capturing and combusting methane; generating renewable energy (thereby reducing dependence on fossil fuels); sequestering carbon by land applying nutrient rich digestate; and diverting organics from landfills (thereby decreasing methane production and release).

   AD projects help communities become more sustainable by producing renewable energy thereby offsetting the need for purchased energy.

B) Protecting America's waters: Use of AD systems protects America's waters by providing a sewage sludge treatment step and facilitating subsequent nutrient recovery.

   The anaerobic digestion of sewage sludge from wastewater treatment facilities plays an important role in cost-effective wastewater solids treatment and management at thousands of facilities due to the significant reduction in solids volume and their stabilization. If energy recovery systems are added, AD provides the opportunity for many of these facilities to offset their energy use.

   Anaerobic digestion concentrates nutrients such as nitrogen and phosphorus, which, if discharged in excess quantities, can cause algae growth and eutrophic conditions in water bodies. These concentrated nutrients can then be recovered and beneficially used. With proper post-digestion nutrient management, AD systems improve water quality.

C) Advancing sustainable development:

   AD projects support sustainable, resilient, and livable communities by reducing fossil fuel consumption; producing a local source of renewable heat, electricity and/or fuel; lessening odors; and strengthening the local economy by reducing energy costs and generating revenue.

   AD projects may conserve resources and increase sustainable materials management by reducing the volume of wasted food disposed of in landfills, since food is a large component of landfilled municipal solid waste (MSW).

   AD may produce liquid and solid products that can be used as fertilizer or soil amendment, replacing some conventional fertilizer.

D) Preventing pollution:

AD may prevent pollution by diverting organics from landfills and agricultural sites, reducing nutrient runoff, and hauling costs.

Prevention of pollution is also achieved at the end of the process, through the production of natural soil amendments. Use of soil amendments can reduce the need for synthetic fertilizers (which require significant energy to produce), reduce the need for pesticides, and/or increase water retention properties when applied to farmlands.

AD can also help EPA pursue the following cross-agency strategies:

A) Working towards a Sustainable Future:

Sustainable Materials Management: There is an increased focus on the benefits of diversion of organics from landfills. Anaerobic digestion of wasted food is a materials management option that can generate energy, reduce GHG emissions and create nutrient rich soil amendments. EPA is engaging and empowering stakeholders by sharing programs, tools, and resources that support AD projects for wasted food.

B) Working to Make a Visible Difference in Communities:

Strengthening EPA's community of practice by leveraging opportunities to coordinate with other federal agencies to provide tools and resources to support AD projects. EPA is actively engaging with USDA and DOE on the President's Methane Reduction Strategy, a key component of which is the development of the Biogas Roadmap.

Applications of AD

Generalizations about anaerobic digester systems often overlook variations. There are many sizes, styles, and applications of digesters. AD systems can be house-sized or town-sized. They can be used primarily for waste processing or energy generation.

Anaerobic digester systems can be designed to optimize mixing, volume reduction, biogas production, pathogen destruction, vector attraction reduction, and odor control. Systems can be designed as batch or continuous flow systems, within a sealed vessel or holding tank, or with a series of vessels (see Appendix A).

Anaerobic digestion processes come in different configurations. Low rate anaerobic digesters are usually used for small systems (under 1 million gallons per day), usually contain no auxiliary mixing, and are operated at long sludge retention times (SRTs) in the 30-60 day range. High rate systems are more commonly used and are

characterized by supplemental heating, auxiliary mixing, uniform feeding rates, and sludge thickening before digestion (WEF, 1998). They are designed for mesophilic temperatures (86-100^{o} F), the most common configuration in North America, at SRTs in the 12-25 day range; or thermophilic temperatures (122-140^{o}F) at SRTs in the 10-12 day range.

Two-stage anaerobic digester systems include a first stage (mesophilic or thermophilic), where most of the gas is produced, and a second stage used for solid-liquid separation or as a holding tank before dewatering. Temperature-Phased anaerobic digestion configurations combine in one system both mesophilic and thermophilic digestion stages connected in series and can offer significant advantages including significantly improved volatile solids reduction and biogas production. Two-phase AD systems are also available with the first stage being an acid phase reactor and the second phase being a methanogenic reactor. Three and multi-stage configurations are also available. Each AD alternative has advantages and disadvantages (Kalogo and Monteith, 2008).

Digesters can handle a variety of feedstocks. Some digesters are designed for one feedstock but may be adapted to other feedstocks or a combination of them. Co-digestion of sewage sludge with other feedstocks (e.g. fats, oils & grease (FOG), wasted food, cheese or wine wastes, manure) can increase biogas production.



Co-digestion can significantly increase biogas production and possibly volatile solids reduction depending on the type of organic feedstock added and other factors (Parry, 2014).

Economic feasibility of co-digestion is strongly dependent upon waste characteristics, regional energy costs, and biosolids residual management costs. Most waste streams (perhaps with the exception of FOG) require a tipping fee paid to the digester owner to achieve economic feasibility. Facilities considering co-digestion should consider utilizing existing process capacity prior to exploring construction of additional capacity for co-digestion (Parry, 2014).

Feedstocks are converted to biogas and digested material, which reduces their volume. The volume reduction and gas production is dependent on the specific feedstock and process.

In addition to the digester there may be additional equipment/technologies needed, either upstream for particle size reduction, de-packaging, screening or moisture adjustment. Downstream of the digester further processes may be needed to clean the gas or modify the digestate into value added products to achieve the desired results in any particular location.

Anaerobic digestion systems may be enhanced by using pre-treatment of the feedstocks or by using different modifications or configurations of anaerobic digestion. Pretreatment methods include thermal, mechanical, chemical, biological, ultrasonic, and combinations of these methods. These pretreatments make the feedstock more accessible to anaerobic microorganisms. No single pretreatment technology is suitable for all anaerobic digestion systems and feedstocks.

Digesters produce biogas:



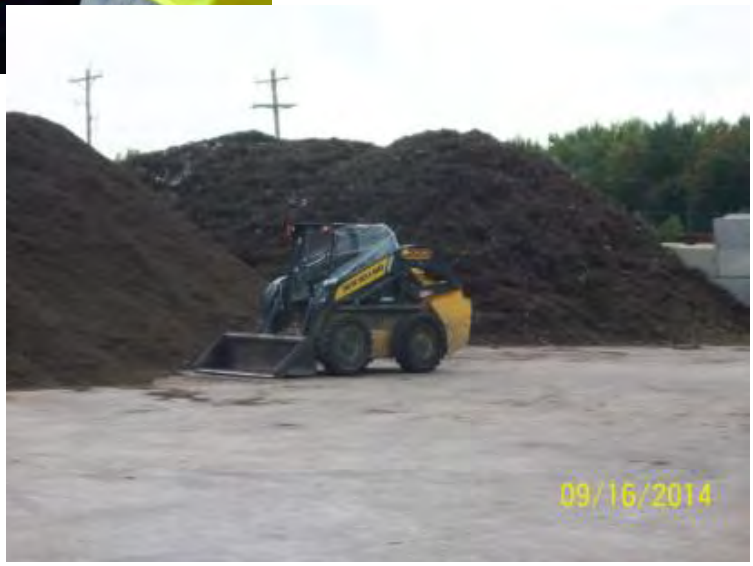
- Biogas is the gaseous product of AD.
- Biogas tends to be about 60% methane. Directly out of the digester it may contain water, hydrogen sulfide, carbon dioxide, and other gases.
- Biogas can be:
    - burned to generate electricity,
    - burned to produce heat,
    - compressed for vehicle fuel,
    - added to natural gas pipelines, or sometimes
    - a combination of those uses.
- Biogas may require cleaning, drying, or other processing to meet a specific use.
- Some generators of the biogas may flare (waste) the gas.
- The amount of biogas production will vary based on feedstock, operation, and process design.

Digesters produce digestate:

- Digestate refers to any non-gas products coming from a digester, which in some cases is separated into liquid and solid streams.
- The end uses of digestate are usually chosen based on its quality (e.g. nutrients, degree of pathogen reduction), and local conditions including market demand.
- Digestate can be rich in nitrogen (particularly ammonia) and phosphorus. Technologies are available to recover ammonia and phosphorus and produce fertilizer products.
- Digestate uses include:
    - soil amendment, direct land application;
    - soil amendment, processed, bagged, and sold;
    - animal bedding; and
    - alternative daily cover for landfills.
- Some digestate needs further processing before it can be used for certain purposes. This processing can include drying or composting.



- Except for digestate made using sewage sludge, there are currently no national standards for the classification of digestate products. Code of federal regulations 40 CFR Part 503 governs the standards for final use and disposal of sewage sludge and derived products.



Factors influencing AD Applications



Anaerobic digestion is one of several integrated waste and organic materials management choices. Other choices include landfilling, composting and thermal processes. Landfilling produces gas as anaerobic digestion takes place within the landfill, but as this AD is largely uncontrolled, it is very inefficient and often leads to unintended releases of methane to the atmosphere.

The following factors have been observed to affect the economics and operations of anaerobic digestion systems:

- The economic viability of an anaerobic digestion project depends on the type and availability of feedstock, regional price of energy, the cost and type of transportation, amount of biogas produced, local air quality standards, tipping fees received for co-substrates, availability of GHG reduction or other credits, incentives and subsidies, and the quality and local demand or options for utilization for resulting products.
- Seasonality of operations (i.e. wet vs dry or hot vs cold).
- Geography (i.e. temperate vs arid climate, or proximity to food processing manufacturers, population centers or farmland).
- Regulations/Legislation
- Other market forces (e.g. competition with low tipping fees at a nearby landfill).

Comparisons between AD systems are complicated, difficult, and dependent on local variables. There are often multiple acceptable choices depending on timing, population, and area of the country. Instead of choosing one system over another, the optimal solution may involve the integration of multiple system types.



Current AD facilities in the US

As of August 2015, www.biogasdata.org estimates there are over 1270 sewage treatment facilities producing biogas.[1]



As of January 2015, EPA's AgSTAR program estimates that there are approximately 247 anaerobic digester systems operating at commercial livestock farms in the United States.[2]



EPA tracks anaerobic digestion facilities that process food-based materials[3]. As of September 2015 there are 98 such facilities in operation. Included in this facility count are municipal food digesters, single source industrial digesters, codigesters on farms and ADs at WWTPs.

[1] Numbers of AD systems at WWTPs are from 2013 EPA and WERF documents (http://www.biogasdata.org/)

[2] Number of Agricultural AD systems reported by the EPA's AgSTAR program. http://www.epa.gov/agstar/projects/index.html

[3] ***Food-based materials include, but are not limited to***: Food scraps that have been separated and collected by municipalities from residential sources; food scraps that have been separated and collected from institutions or venues (prisons, hospitals, stadiums, etc.); food scraps from food preparation at restaurants, cafeterias, and other food services; plate scrapings from restaurants, cafeterias, and other food services; Fats, oils and greases; unused food collected from grocery stores (bakery items, bruised fruit, items passed shelf life, etc.); and pre-consumer by-products of the food and beverage processing industries.

References

Metcalf & Eddy., Tchobanoglous, G., Burton, F. L. 1., & Stensel, H. D. (2003). *Wastewater Engineering: Treatment and Reuse* (4th ed.). Boston: McGraw-Hill.

Water Environment Federation – WEF – (1998). *Design of Municipal Wastewater Treatment Plants*, 4th Edition, Manual of practice No. 8: Alexandria, VA, U.S.A.; American Society of Civil Engineers, Manual on Engineering Practice No. 76: New York, U.S.A.

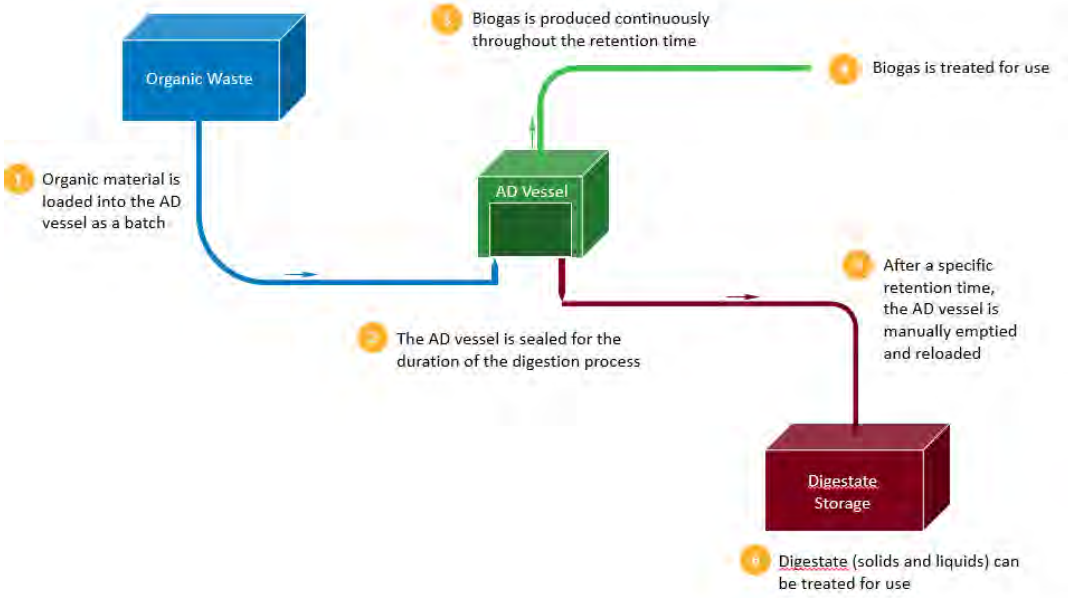
Kalogo, Y, and Monteith, H.P., Water Environment Research Foundation – WERF – (2008). *State of Science Report: Energy and Resource Recovery from Sludge.* Jointly funded by WERF, UK Water Industry Research Limited, STOWA and sponsored by the Global Water Research Coalition (GWRC). Alexandria, VA, U.S.A.

Parry, D.L., Water Environment Research Foundation – WERF – (2014). *Co-Digestion of Organic Waste Products with Wastewater Solids – Final Report with Economic Model*. Alexandria, VA, U.S.A.

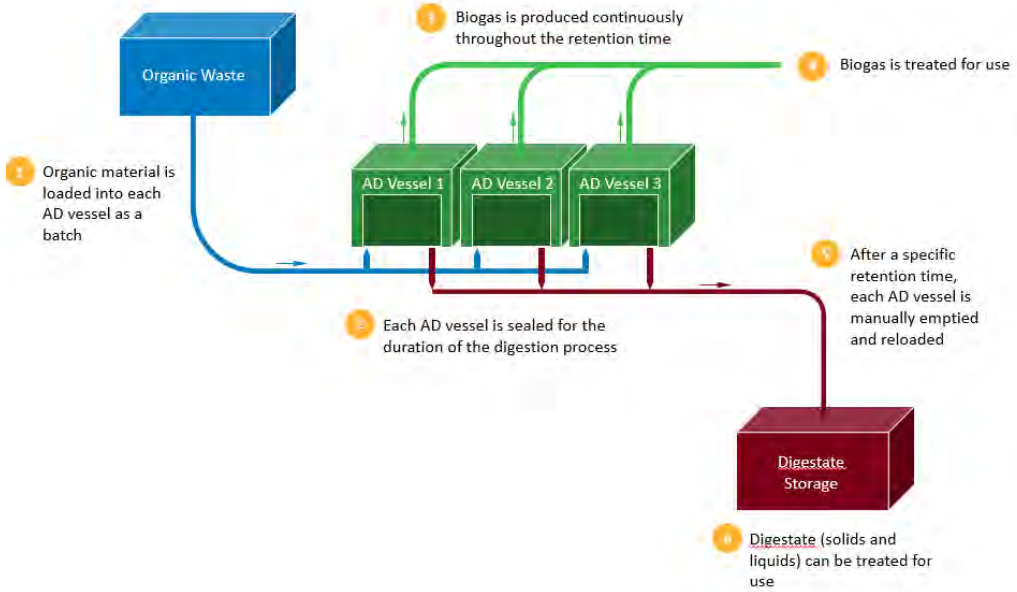
Jones, R. et.al, *Characterization of Sludges for Predicting Anaerobic Digester Performance*. Water Science & Technology—WST **Vol 57 No 5 pp 721–726** © IWA Publishing 2008.

Appendix A: System Diagrams

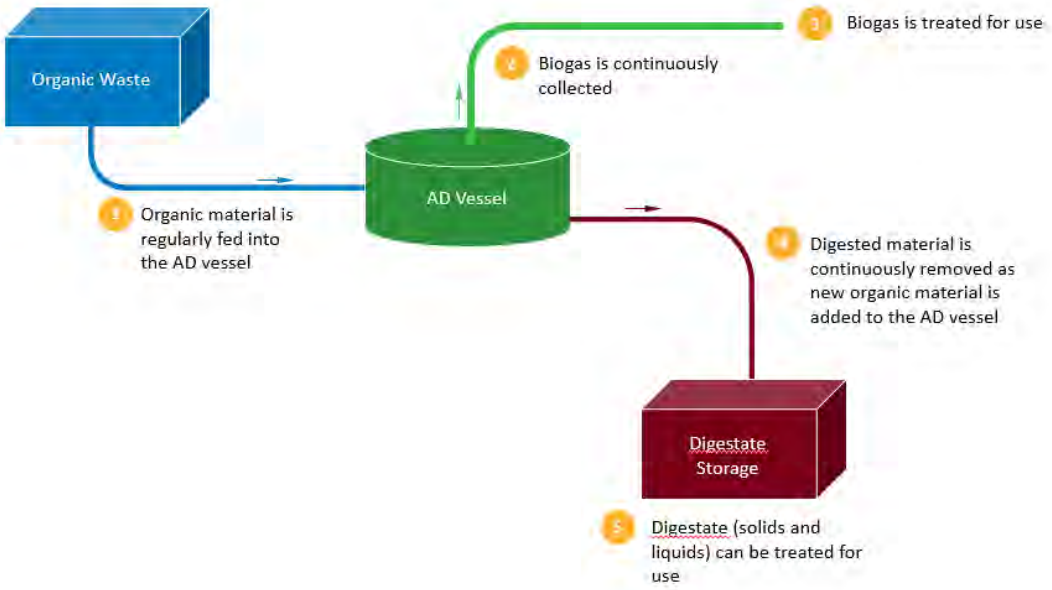
Batch System with a Single Vessel



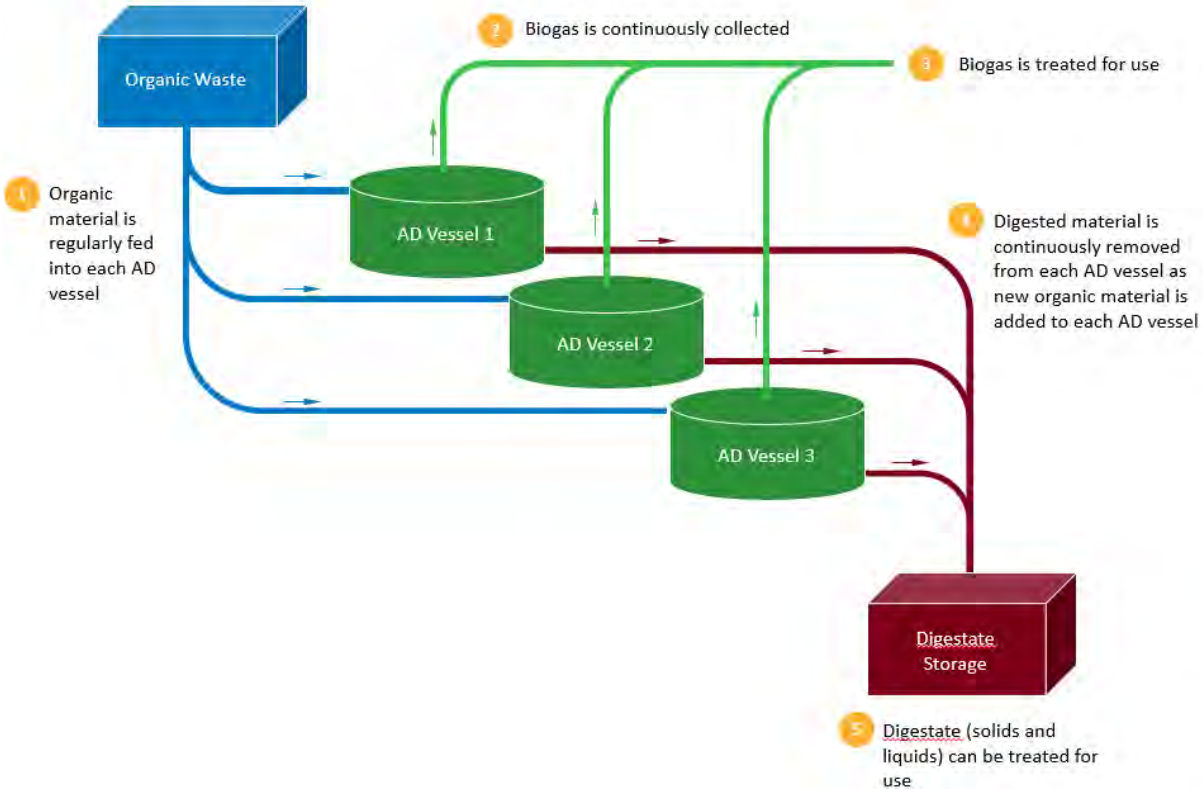
Batch System with Multiple Vessels



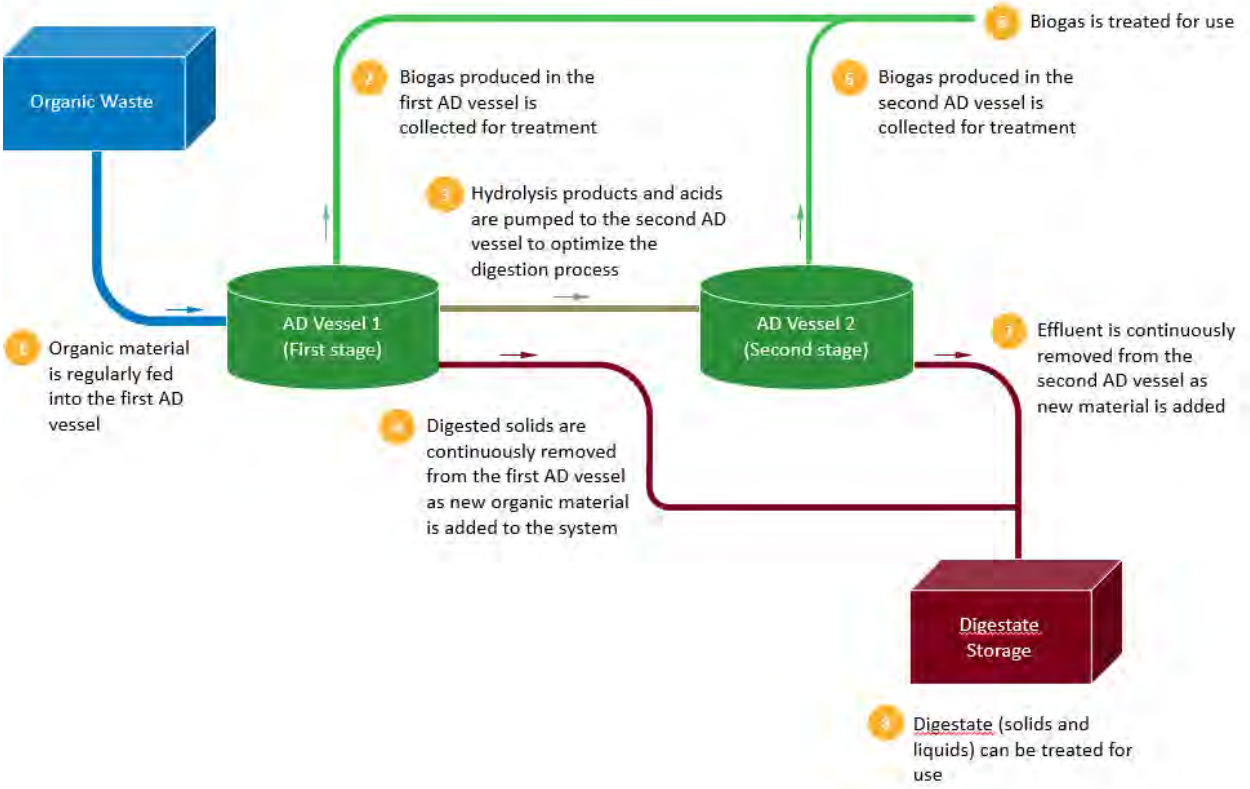
Continuous Flow System with a Single Vessel



Continuous Flow System with Multiple Vessels



Phased Continuous Flow System with a Series of Vessels



Glossary

acetogenesis: The third of four biological steps in anaerobic digestion. The process by which volatile fatty acids are converted into acetic acid, carbon dioxide, and hydrogen.

acidogenesis: The second of four biological steps in anaerobic digestion. The process by which simple monomers are converted into volatile fatty acids. Also referred to as a fermentation step.

aerobic digestion: is the biochemical decomposition of organic matter into carbon dioxide and water by microorganisms in the presence of air.[4]

anaerobic digester: an anaerobic digester is a built system for excluding oxygen from organic material and producing biogas.

anaerobic digestion: is the biochemical decomposition of organic matter into methane gas and carbon dioxide by microorganisms in the absence of air.[5]

biogas: is a mixture of approximately 60% methane (CH4) and 40% carbon dioxide (CO2) together with trace levels of other gases. Biogas is produced when organic material is broken down by microorganisms in an oxygen free, or anaerobic, environment.

codigestion: The digestion of two or more feedstocks in a single anaerobic digestion system.

composting: composting is an aerobic process of using microbial communities to degrade organic material.

feedstocks: any material used in an AD system can be considered a feedstock. Typically AD feedstocks include manure, silage, sewage sludge, wasted food, yard waste, FOG, and industrial organic byproducts. waste

high solid AD systems: greater than 15% solids (by volume) content.

hydrolysis: The first of four biological steps in anaerobic digestion. The decomposition of organic compounds by interaction with water.

low solid AD systems: less than 15% (by volume) solids content .

methanogenesis: The process by which acetate is converted into methane and carbon dioxide, while hydrogen is consumed.

[4] Definition cited from 40 CFR 503.31(a)

[5] Definition cited from 40 CFR 503.31(b)



EPA
United States
Environmental Protection
Agency

PRESORTED
STANDARD POSTAGE
& FEES PAID EPA
PERMIT NO. G-35

Office of Research and
Development (8101R)
Washington, DC 20460

Official Business
Penalty for Private Use
$300