ON-FARM CO-DIGESTION OF DAIRY MANURE WITH HIGH ENERGY ORGANICS

Stakeholder Interviews and Literature Review (Anaerobic Digestion Systems Series)

FS172E

ON-FARM CO-DIGESTION OF DAIRY MANURE WITH HIGH ENERGY ORGANICS

By
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Abstract

The Anaerobic Digestion Systems Series provides research-based information to improve decision-making for incorporating, augmenting, and maintaining anaerobic digestion systems for manure and food by-products. Anaerobic digestion is a waste treatment process that occurs in an oxygen-free environment. In this process, microorganisms convert organic materials to biogas, a source of renewable energy. Besides producing energy, anaerobic digestion helps solve many environmental concerns associated with wastes, including odors, pathogens, greenhouse gas emissions (GHG), and air and water quality issues. At dairies and other livestock operations, the manure can be purposely mixed with other organic material such as pre-consumer food wastes to improve biogas yield, economics, and the AD process. This publication defines the co-digestion process and discusses major advantages and disadvantages.

Table of Contents

On-Farm Co-Digestion of Dairy Manure with High Energy Organics

List of Abbreviations

AD	Anaerobic Digestion
ATA	Anaerobic Toxicity Assay
BMP	Biochemical Methane Potential
C/N	Carbon to Nitrogen Ratio
CAFO	Concentrated Animal Feeding Operation
DAF	Dissolved Air Flotation
FOG	Fats, Oils, and Greases
GHG	Greenhouse Gas
HRT	Hydraulic Retention Time
K	Potassium
N	Nitrogen
NMP	Nutrient Management Plan
P	Phosphorus
REC	Renewable Energy Credits
RNG	Renewable Natural Gas
SDSS	Spatial Decision Support System
TAN	Total Ammonia Nitrogen
TKN	Total Kjeldahl Nitrogen
TP	Total Phosphorus
U.S.	United States

Introduction

Anaerobic digestion (AD) is a biochemical waste treatment process that occurs in an anaerobic environment (without oxygen), in which microorganisms convert complex organic materials to biogas, a source of renewable energy. In addition to producing energy, the process mitigates many environmental concerns associated with organic residuals and wastewaters, including odors, pathogens, greenhouse gas emissions (GHG), and air and water quality issues. At dairies and other livestock operations, co-digestion, the practice of purposefully supplementing the manure feedstock with multiple forms of organic material (known as substrates), is often used to improve biogas yield, economics, and the AD process. Figure 1 illustrates the dairy AD process under a co-digestion scenario. The main products include fiber (often used as animal bedding), biogas (combusted to produce electricity and heat), and effluent (land applied as a fertilizer).

Each of these products can be further processed using add-on technologies to produce higher value co-products, such as horticultural fiber, renewable natural gas (RNG), and fertilizer products.

The number of digesters on dairies in the United States has steadily increased, but the technology is still not common. As of September 2014, there were an estimated 193 dairy based digesters operating on commercial dairy farms—serving an estimated 4% of dairy cows (AgStar 2014; USDA-ERS 2013). Unfortunately, in many regions of the U.S., including the Pacific Northwest, new and existing manure-based AD projects have been hindered by decreasing revenue (Novak 2012). Most manure-only AD projects receive revenue from up to four sources: electrical sales, fiber sales, carbon credits, and renewable energy credits (RECs)—with electrical sales the largest contributor to revenue. Yet, only revenue from fiber has remained steady in recent years (Coppedge et al. 2012). Carbon credits and RECs have been highly volatile due to market fluctuations and regulatory uncertainty. Meanwhile, received electrical prices have decreased across the nation, due in part to breakthroughs in domestic natural gas extraction, which have driven down received electrical prices for renewable energy projects across the U.S.

In the Pacific Northwest, these forces have dropped traditionally low, hydroelectric-driven electrical rates even lower (Coppedge et al. 2012). For example, the largest dairy AD project in eastern Washington was paid $0.07 per kWh in 2012. In 2013, when a new power purchase agreement was formed, this rate fell to $0.04 (Coppedge et al. 2012). Similarly, in Oregon, received electrical rates dropped to around $0.05 per kWh in 2012, slowing the development of projects in the state (Sullivan 2012).

Challenges to AD project profitability have led to increased interest in methods for generating additional revenue at dairy manure-based anaerobic digesters by farmers, third party project developers, and regulatory agencies. This publication provides information on co-digestion with high-energy organic substrates—one business model that is being used to benefit AD project profitability. The emphasis is on dairy manure digesters, though lessons learned can be adapted for other organic residual and wastewater digesters. A companion publication entitled *Considerations for Building, Operating, and Maintaining Anaerobic Co-Digestion Facilities on Dairies* (Kennedy et al. forthcoming) provides stakeholders with an understanding of the impacts of co-digestion on AD project operation. In addition, *Anaerobic Digestion Effluents and Processes: The Basics* (Mitchell et al. 2015) offers basic information on the AD process.

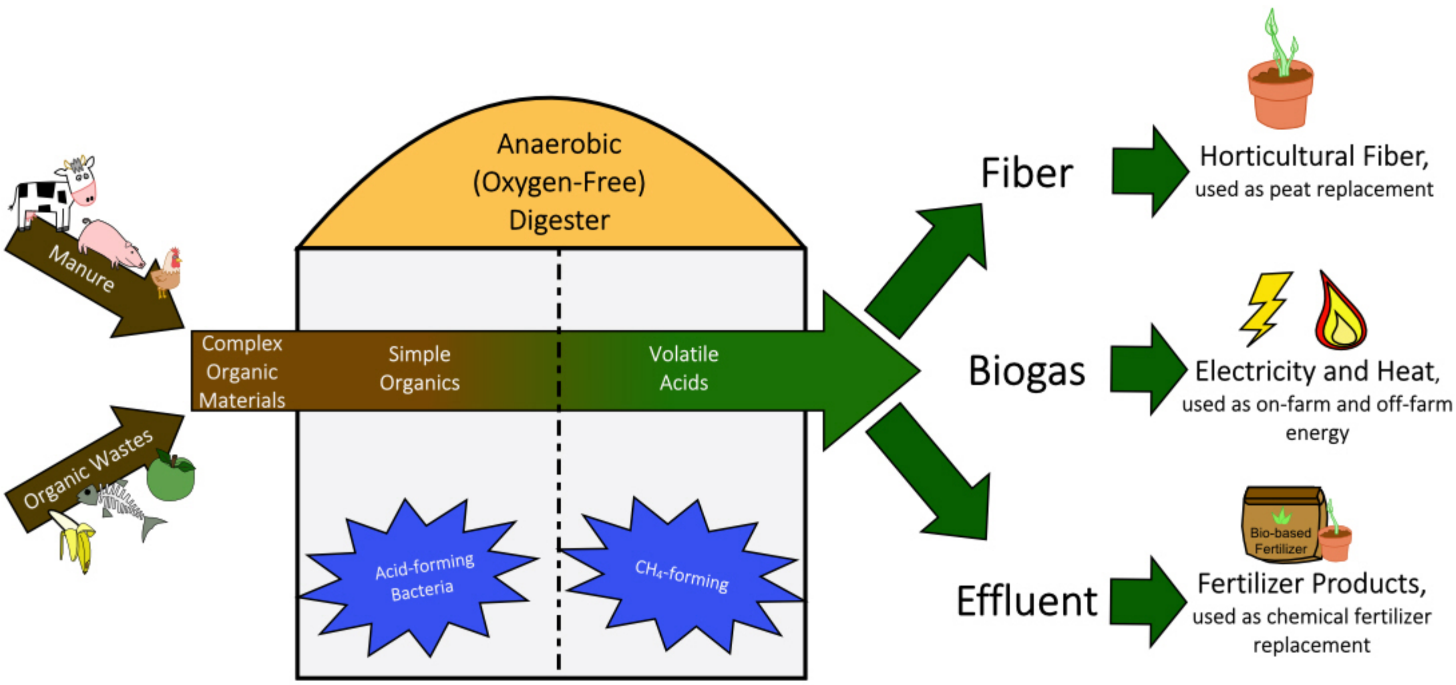

Figure 1: Overview of AD process. Graphic by Georgine Yorgey and Nicholas Kennedy.

To provide an insider's look at design and management considerations, five individuals with extensive experience in co-digestion at dairy digesters were interviewed. Interviewees included a scientist with in-depth knowledge of AD and co-digestion (A), two systems engineers who have designed numerous digesters that incorporate substrates (B and C), a dairy farmer who owns and operates a co-digestion facility (D), and a project developer who has successfully implemented co-digestion at a number of dairy digesters (E). The sample size was relatively small because few individuals have technical expertise in co-digestion in the U.S., and some of these candidates were not willing to be interviewed. Several of the sources work primarily in the Pacific Northwest where the authors are located; however, to the extent possible, individuals with broader experience throughout the U.S. were included. To preserve anonymity, interviewees are labeled as A, B, C, D, and E as indicated above. Highlighted tips from these industry experts are included throughout for quick reference.

Overview of Co-Digestion Process

During co-digestion on dairies, energy-rich organic waste materials are added to the main manure wastewater input (AgStar 2012). From a practical perspective, co-digestion is very similar to manure-only AD, with a few infrastructure upgrades and process changes potentially being required (Figure 2).

While costs are site specific and vary based on a number of factors, necessary enhancements for effective operation of co-digestion projects typically raise both capital and operating costs by roughly 10% against a manure-only baseline (Astill et al. 2014). Typical requirements are described briefly, and are covered in significantly more detail in *Considerations for Building, Operating, and Maintaining Anaerobic Co-Digestion Facilities on Dairies* (Kennedy et al. forthcoming).

Substrates are hauled to the digester by the waste producer, third party contractor, or the AD operator. In some cases, tipping fees are received for accepting the wastes. Detailed substrate delivery logs (usually with weights or volumes, but not necessarily with a dedicated scale) are important since contracts are usually tied to tipping fees and substrates may be regulated (A).

After delivery, organics may be pre-treated or pre-screened (or both). In the U.S., most AD projects currently use substrates that do not require extensive pre-treatment or pre-screening, including pre-consumer food wastes, food processing wastes, milk processing wastes, and similar materials. Notably, high-solids or post-consumer food waste would require a considerably higher degree of pre-screening to remove inert packaging materials, plastics, glass, and metals. Fibrous residues or dedicated energy crops, already frequently used in Europe, similarly might require more extensive pre-treatment or larger digesters with extended hydraulic retention times (HRT), so as to overcome their recalcitrant lignocellulosic composition (Murray et al. 2014).

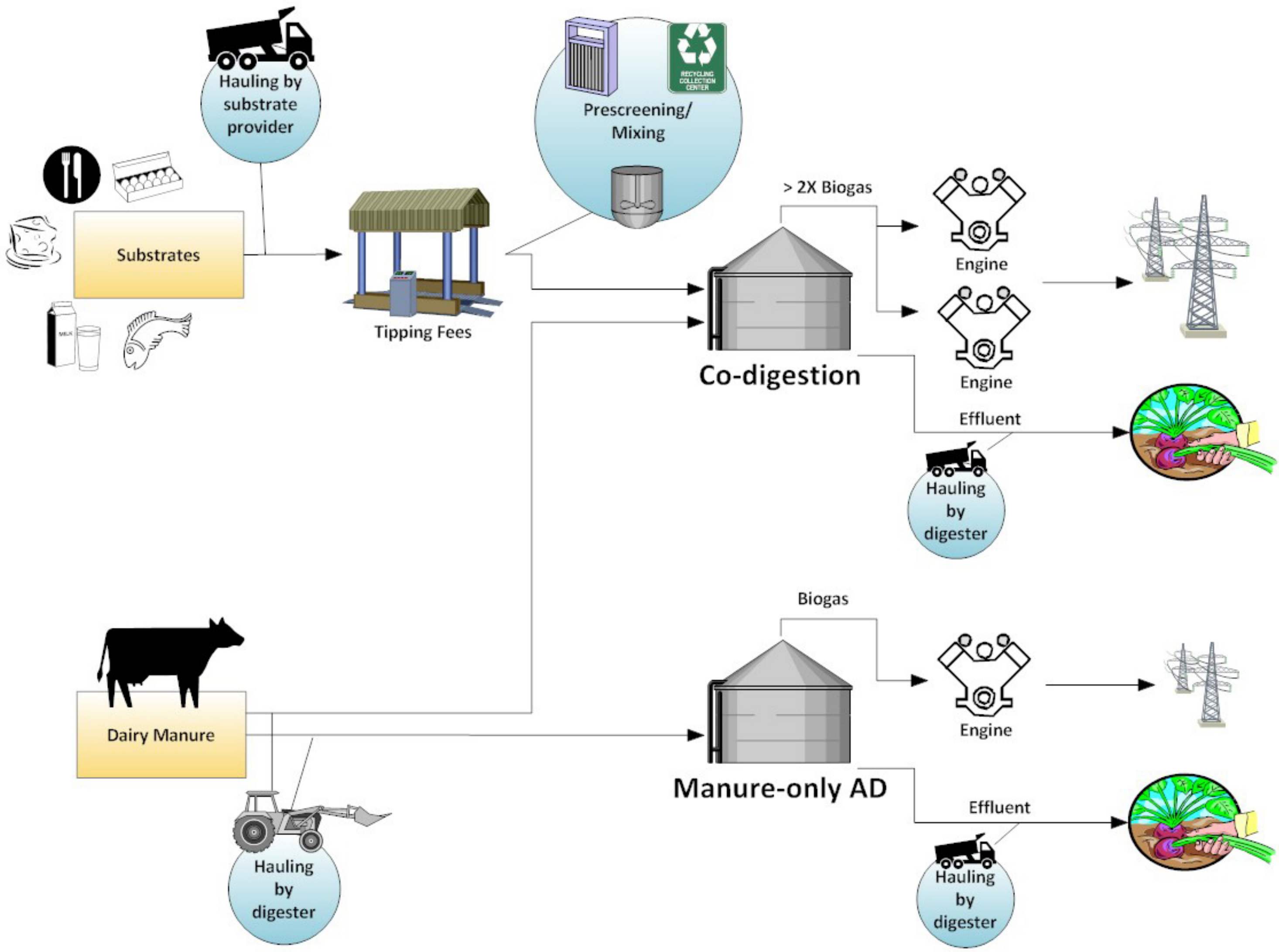

Figure 2: Co-digestion and manure-only AD. Graphic by Nicholas Kennedy.

After any pre-treatment and pre-screening, the substrate is loaded into a receiving pit where it is mixed and introduced into the digester via pumps, either all at once or on a metering system that better controls the flow rate of the substrate (A, B, E). Depending on the type of substrate and digester, other infrastructure upgrades to the digester, receiving pits, and engines may be necessary. Biogas is generated through the co-digestion process, at increased rates compared to manure-only digesters. In the U.S., the biogas is currently most commonly used to generate electricity and heat, though upgrading biogas to RNG is also possible. Economics of RNG compared to other end uses is covered in *Anaerobic Digester Project and System Modifications: An Economic Analysis* (Galinato et al. 2015), and technologies for upgrading to RNG are covered in *Biogas Upgrading on Dairy Digesters* (Kennedy et al. 2015).

Major Advantages and Disadvantages of Co-Digestion

On their own, the energy content of manures is rather low. This is because a portion of the organic material is reduced in energy content due to earlier digestion in a cow's rumen (A). Thus, for example, at an average biogas yield of 20 to 30 m^3/wet metric ton, manure-based AD projects only just meet the required amount of biogas that is needed to offset capital costs and provide profitability (DEA 1995).

In contrast, co-digestion typically uses organic waste material that retains higher energy content, increasing biogas and methane production. Depending upon the type, concentration, and flow rate of the substrate used, biogas production can be enhanced by 25 to 400% (Alatriste-Mondragón et al. 2006; Braun et al. 2003; Frear et al. 2011). Variation in the increases achieved results from the type of substrate and other factors. Figure 3, showing data derived from a study at Cornell University, illustrates the vast difference in methane output from different substrate types.

In addition to benefitting biogas production, substrates can also benefit the dairy AD process itself. At proper volumes and types, substrates can have positive synergies with dairy manure.

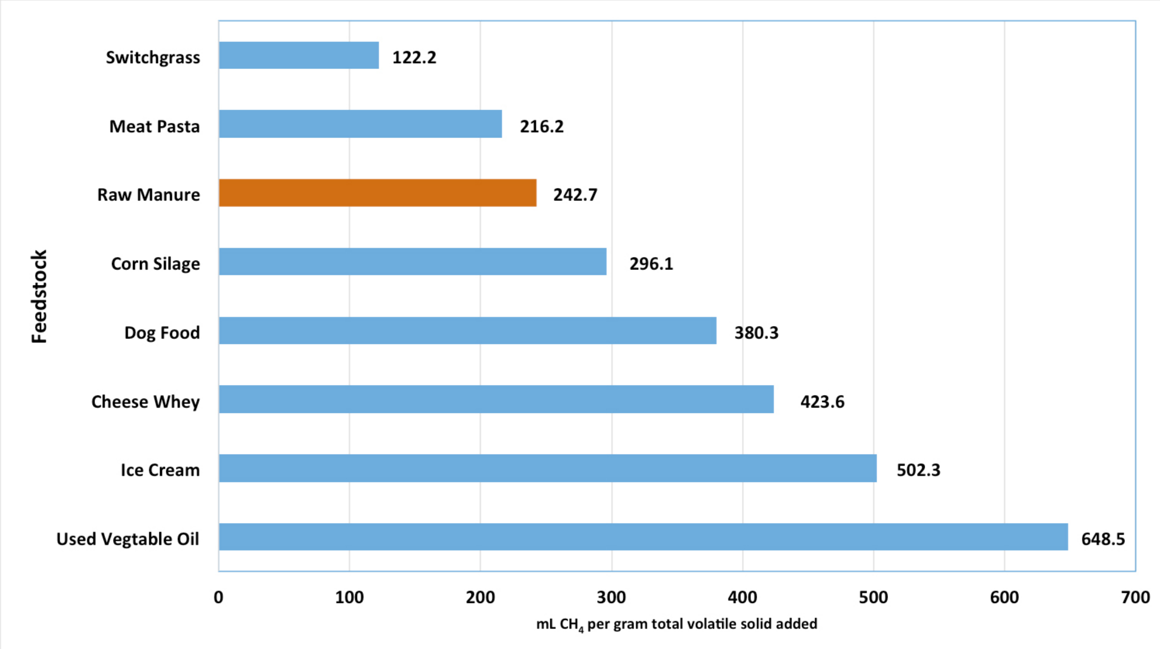

Figure 3: Methane yields of various substrates. Modified from Labatut and Scott 2008.

Substrates improve carbon to nitrogen (C/N) ratios, nutrient balances, and benefit other chemical parameters that improve the chemical environment, methane yield, and process stability (Frear et al. 2011). Careful consideration of how substrates are added to the digester is critical to ensure healthy AD and reduce the risk of digester upset (A, D, E). Some of the known advantages and disadvantages of co-digestion are summarized in Table 1 (Carucci et al. 2005; Lehtomaki 2007; Steyer et al. 2006).

Industry Tip: It is beneficial to have an estimate of the biogas production potential of a substrate when co-digested with manure prior to adding it to a digester. Existing estimates, available for most substrates via reports and scientific publications, can give a good indication of how a substrate will impact a digester project prior to performing tests or introducing it into the digester.

Types of Substrates

A wide range of organic wastes can be successfully co-digested with dairy manure as long as they are added at appropriate volumes and rates (Atandi and Rahman 2012; Camarillo et al. 2013; El-Mashad and Zhang 2010; Frear et al. 2011). Anaerobic microorganisms are versatile and have the ability to breakdown most, but not all, organic substrates. For example, woody material is not very easily digested due to its lignocellulosic composition (Atandi and Rahman 2012).

Table 1: Advantages and Disadvantages of Co-Digestion, as Summarized by Carucci et al. 2005; Lehtomaki 2007; Steyer et al. 2006; and interviewees.

Advantages	Disadvantages
• Organics diverted from entering landfills • Improved overall process economics (higher biogas production and revenue from tipping fees and renewable credits) (A, D, E) • GHG emissions reductions • Improved fertilizer value of the digestate (less solids due to higher degradation) • Synergistic effects with substrate combinations leading to improved carbon to nitrogen (C/N) ratio, nutrient balances, and other chemical parameters	• Biological inhibition and process upsets (decreased biogas production or digester failure) that can occur from chemical, biological, and physical constituents within the waste being co-digested (e.g. soaps, polymers, etc.) (E) • Inorganic material (e.g. plastics, metals, sand, etc.) that can negatively impact the digester performance via clogging (B, C) • Excessive scum from flotation and mixing problems due to fats and oils • Higher production of biogas contaminants (hydrogen sulfide and carbon dioxide) (C, D, E) • Increased nutrients, such as nitrogen (N), phosphorus (P), and potassium (K) from substrates can be problematic for farmers' nutrient management plans (NMP) (A, B, C, D, E) • Additional regulations (D)

Table 2: Organic Material that Digests Well and Organic Material to Avoid (in no particular order) (A, B, C, D, E)

Substrates to Target		Substrates to Avoid
• Food processing wastes (e.g. potato, onion, fish, tomato, maize, meat) • Waste glycerol • Milk processing wastes (e.g. yogurt, cheese, butter, whey, lactose) • Waste or spoiled milk • Distillery waste • Egg breakage • Breading • Brewery waste • Pre- and post-consumer food scraps • Out of date sugar and alcoholic beverages	• Fats, oils, and greases (FOG) (if appropriate concentrations and types) • Animal waste (e.g. dissolved air flotation [DAF]) • Food processing DAF (chicken, fish, milk yogurt) • Blood • Paunch manure • Fruit juice • Fruit pomace • Animal feed waste • Biofuel processing waste (e.g. Jatropha, mustard oil cake) • Soda • Green waste (e.g. grass clippings)	• Straw, unless macerated • Wood chips (clogging and degradability issues) • Sticks (clogging and degradability issues) • Plastic (clogging and degradability issues) • Metal (clogging and degradability issues) • Rubber (clogging and degradability issues) • Grocery waste, unless clean and source separated (could cause clogging) • FOG (can cause digester failure depending on type and concentration)

Keeping this in mind will maintain a healthy AD process and reduce operational problems (A, D, E). Table 2 provides a list of common substrates that have been successfully utilized at dairy manure digesters and known substrates that should be avoided or used with appropriate caution.

Though a wide range of substrates can be used successfully, several individuals involved with co-digestion projects indicated that some of the most important factors in determining what a project co-digests, and how well co-digestion is carried out over time, include location, hauling distance, type and volume of substrates attainable, and consistent long-term availability (A, D, E). These identified factors are juxtaposed with economic considerations related to availability and value of tipping fees. Given these numerous factors, substrates with high tipping fees are not always the best choice for a project (A).

Industry Tip: A project targeting substrates with great biogas potential (such as food scraps) should answer a number of questions. How fast does the organic waste digest? Will the organic waste change the pH of the digester? Will the organic waste cause inhibition? And how will the organic waste impact nutrients?

Regulatory Limitations on Substrates

Some states have regulations that limit the type and amount of substrates allowed or specify the degree of pretreatment required.

Figure 4: Pre-consumer food waste is an excellent substrate for co-digestion as long as there is no contamination with packaging. Photo courtesy of DVO, Inc.

As of 2014, Oregon and Idaho did not have any co-digestion permit requirements, though biological, physical, and chemical limitations do limit the ratio of manure to substrate (See section: Biological, Chemical, and Physical Inhibition Concerns).

In Washington, co-digestion is regulated by the Washington State Department of Ecology and local health departments under WAC 173-350-225, which provides an exemption from a permit under certain requirements. In order to qualify for an exemption from a solid waste-handling permit, a minimum of 50% dairy manure and maximum of 30% pre-consumer food processing waste can be used.

Post-consumer food scraps and certain tissues (e.g. sheep processing wastes) are not exempt and thus require a solid waste-handling permit—adding to management time and costs. See *Anaerobic Co-digestion on Dairies in Washington State: The Solid Waste Handling Permit Exemption* (Yorgey et al. 2011) and WAC 173-350-225, for more information.

Industry Tip: A farmer or project developer should consider that co-digestion projects will be under more supervision by regulatory agencies than manure-only AD projects. This occurs because waste materials from off-farm sources result in more monitoring from health and safety agencies.

Compatibility with Dairy Manure

To maximize co-digestion benefits, it is best to acquire substrates with high energy content and good compatibility with dairy manure in terms of the C/N ratio, alkalinity, pH, nutrients (N, P, K), micro-nutrients, and trace elements, such as sulfur, iron, manganese, magnesium, calcium, nickel, cobalt, copper, and zinc (Amani et al. 2010; Atandi and Rahman 2012; Frear et al. 2011). Optimum C/N ratios of 15:1 to 45:1 are required for successful AD (Atandi and Rahman 2012). Substrates that have a higher C/N ratio can thus be mixed with dairy manure (low C/N ratio) to increase the overall C/N ratio and improve the AD process (see Table 3). In addition, anaerobic bacteria require a delicate balance of macro- and micronutrients. Some of these nutrients are lacking in dairy manure and can be added with substrates. Table 3 shows how substrates can be used to achieve improved input parameters for AD and higher biogas and methane production.

Industry Tip: It is helpful to think of the microbes in a digester as being similar to a new type of livestock. You need to create conditions that are optimal for microbial growth so they can grow well and perform their job efficiently. A balanced diet, achieved with careful choice of substrates, will help ensure that the digester performs optimally.

Biological, Chemical, and Physical Inhibition

Efficient AD requires balanced conditions that meet contrasting nutritional and environmental conditions needed for both acid-forming and methane-forming microorganisms (Pohland and Ghosh 1971). The presence of inhibitory substances can upset this balance, leading to digester instability, upset and failure (A, B, C, D, E). Inhibition can be caused by biological inhibitors (e.g. FOG, ammonia), chemical inhibitors (e.g. antibiotics, antifungals in cardboard), or physical inhibitors (e.g. straws, sawdust, insoluble starches, struvite formation in pipes, inert material) (A). In thinking about inhibition, consideration of all substrates and their possible interactions when mixed is important (A, B, C, D).

Among biological inhibitors, lipid-rich wastes such as FOG are highly desirable co-digestion substrates because of their relatively high methane yield and synergies when co-digested with dairy manure. However, due to the possibility of inhibition, it is recommended to limit FOG to less than 10% of total solids input (A). In addition, high amounts of lipids can cause sludge flotation, digester foaming, blockage of pipes and pumps, and clogging of gas collection and handling systems (Long et al. 2012).

Ammonia has also been shown to cause digester inhibition. Koster and Lettinga (1988) found that during AD of potato juice, ammonia concentrations were increased to a range of 4051 to 5734 mg ammonia-N per liter, resulting in a 56.5% drop in methanogenic activity levels and inhibiting biogas production. In some cases, other factors, including pH, presence of ions (e.g. sodium, calcium, and magnesium), temperature, and microbial acclimation, have also been shown to contribute to the severity of ammonia inhibition (Chen et al. 2008).

Among chemical inhibitors, antibiotics can inhibit methane production when they are present above effective concentrations for the AD microbial community (Mitchell et al. 2013). Similarly, anti-fungal agents can inhibit anaerobic microorganisms. Anti-fungal agents are often used in cardboard packaging to prevent fungus and mold growth (A).

Table 3: Example of Balancing AD Input Parameters Through Co-Digestion with Egg Breakage, Fish Breading, Artificial Crab, and Ravioli Sauce (Frear et al. 2011)

Source	C/N Ratio	Alkalinity g $CaCO_3$/L	pH	Nutrients (N:P:K)	Micronutrients Elements
Dairy Manure	11:1	9.63±3.22	6.94±0.08	6:1:6	Fe, Mn, S, Mg, Ca, Ni
Substrate*	56:1	3.39±1.40	5.19±0.96	10:1:1	Se, Ni
Co-digestion	28:1	8.96±1.00	6.87±0.41	8:1:4.5	All

*egg breakage, fish breading, artificial crab, and ravioli sauce

Physical inhibitors typically come from crop residues or other materials with high lignocellulosic content (e.g. straw, sawdust, etc.) (A). Lignocellulosic structures cannot be easily broken down by anaerobic bacteria, resulting in low gas yield (Chen et al. 2008). Particle size of these lignocellulosic materials, either large (un-chopped straw) or small (sawdust), can interfere with mixing and lead to settling or the production of a scum layer (A). In addition, interaction of these materials or other inert materials such as plastics or sand with FOG can produce congealed masses that can interfere with mixing (A, D). Most inert substances can be removed prior to digestion via source separation, while recalcitrant substrates (e.g. straw) can undergo pretreatment to reduce particle size and remove lignin.

When inhibition is a problem, it is most often because the substance was not detected during source separation and pretreatment, the substrate provider was not aware of its inhibitory effects on anaerobic microorganisms, or the processing conditions of the waste stream were altered, introducing an unknown new inhibitory concern (E). Tests such as an anaerobic toxicity assay (ATA) and biochemical methane potential (BMP) can be performed by laboratories and third party contractors to help identify inhibitory potential before a new substrate is introduced to a commercial digester (A, E). These tests are covered in more detail in *Anaerobic Digestion Effluents and Processes: The Basics* (Mitchell et al. 2015).

Industry Tip: If FOG is used as a substrate, the volume will need to be limited to avoid inhibition. Also, high-energy substrates such as FOG take longer to break down, and often require longer HRT. If the HRT is too short, undigested FOG will leave the digester. This will result in a loss of potential energy and negative impacts on fiber quality.

Substrate Procurement Process and Contracts

Substrates can be obtained either directly from the organic waste producer or from a third party waste hauler (D, E). Whether dealing with the substrate provider or a third party hauler, project developers should not underestimate the amount of time and effort that is needed for procuring substrates. Finding the right contacts and developing relationships may take months or even years. Trust is a major driving force in many cases because organic waste producers do not want to be suddenly left with disposal problems resulting from an unreliable disposal service. In addition, in several areas across the U.S., “gentlemen’s agreements” are more common than actual contracts (E). Because technologies constantly change, waste producers and haulers generally prefer to retain the flexibility to divert wastes, if a higher value use is developed or a cheaper disposal option is found (E).

The process is also complicated by the fact that a digester may need several different types of wastes to co-digest optimally. Many commercially available feedstocks, such as agricultural and food processing wastes, may be only available seasonally and on short-term contract basis, requiring co-digestion projects to obtain a variety of different substrates from numerous sources (D, E). Because of the time and expense required to acquire substrates—particularly in cases when several substrates from different sources are being sought—some AD projects rely on third party matchmaking services, which generally negotiate a fee with the digester owner (A). Even when utilizing a third party, the procurement process can still take up to a year or more (see Table 4).

Advantages to using a third party contractor can extend beyond substrate acquisition. For example, if any unforeseen problems arise at the digester, the third party contractor will normally divert the substrates, either by sending the waste to another digester they work with, or by disposing of it elsewhere (D). This ensures that the needs of both the substrate provider and farmer are met until the digester is up and running again (D). Third party contractors can also directly contact the organic waste producer if consistency in substrate composition or volume becomes an issue (D).

Table 4: Estimated Time and Effort Required for Procurement Process, Using a Matchmaking Service.

Source	Estimated Time to Contract	Implementation Category
Grocery Stores	3 to 18 Months	Moderate to Difficult
Hotels/Resorts	1 to 9 Months	Moderate
Food Manufacturer	1 to 3 Months	Easy to Moderate
Grease Trap Services	1 to 3 Months	Easy
Restaurants	1 to 3 Months	Moderate to Difficult

Table courtesy of Organic Solution Management.

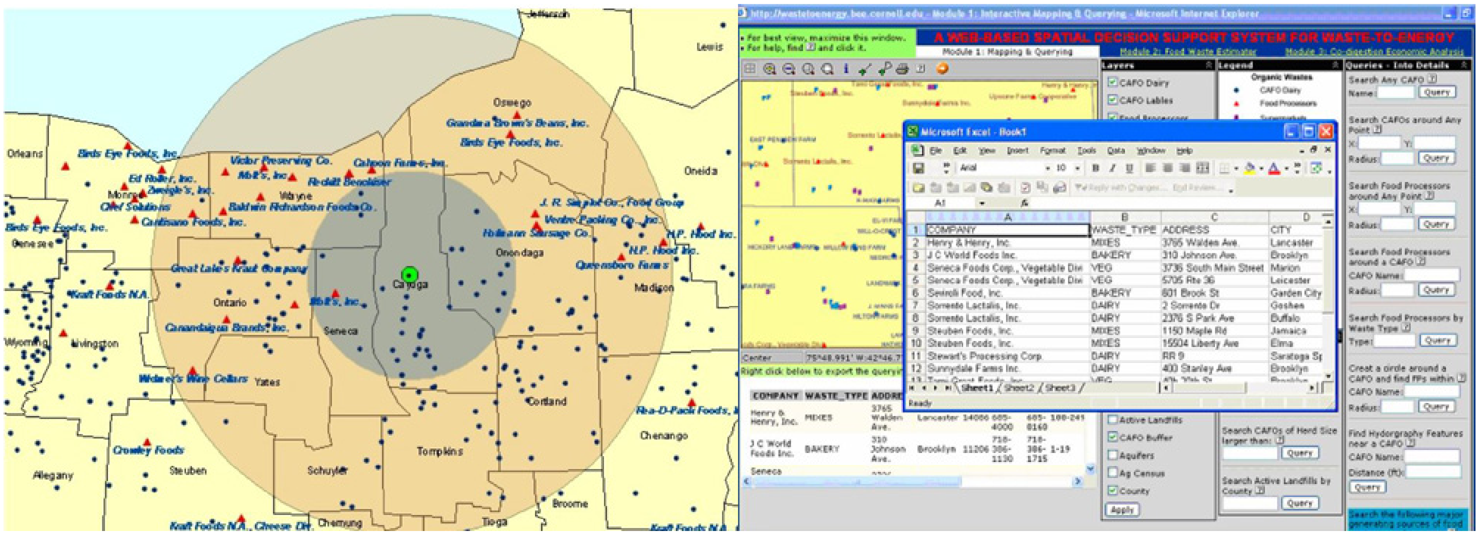

Figure 5: Distribution of food processors within 20 and 50-mile radius of targeted concentrated animal feeding operation (CAFO) (left), and excel file listing all the organic waste producers within the radius set with contact information (right). Note: images were taken in 2006 and may have altered since then (Ma 2006). Images courtesy of Norman Scott.

Industry Tip: Some substrate providers are reluctant to make short and long term contracts with digester projects due to frequent technological advances at processing facilities that may lead to new uses for current "wastes." Unfortunately, this inability to acquire long-term or even short-term contracts can make it more difficult to obtain bank loans for co-digestion projects.

Locating Substrates

Locating substrates within close proximity to a manure-based digester is essential to successful co-digestion because it reduces hauling costs (D, E). Though these costs are most often paid by the waste disposer (not the digester operator), they impact the tipping fees received. In some areas of the country, spatial decision support system (SDSS) tools have been developed and implemented to help project developers easily identify substrates (Ma 2006). Organic waste producers within a specified radius can be identified and categorized by food waste source, waste type, volume, and distance (Ma 2006). Figure 5 illustrates how SDSS was used to provide a farmer with all the organic waste producers within a 20- and 50-mile radius of the dairy in upstate New York. In the absence of such services, third party contractors or others may fill this role.

Industry Tip: Finding a *consistent* and *reliable* source for substrates is critical to successfully implementing co-digestion at dairy digesters.

What To Do When Problems Arise

Even if substrates are successfully located and all necessary tests are used to ensure healthy synergy with dairy manure during AD, problems can occur (E). Substrates can change in composition over time due to changes in technologies, processing techniques, and chemicals (C, E). This is particularly true for substrates that are derived from food processing plants such as milk, fish, and chicken products (E). Unfortunately, inconsistency in composition can be detrimental to digesters, especially if bactericides are added to a substrate (C).

One simple and inexpensive way to help minimize digester upset is to consistently monitor biogas production by tracking the flow rate with a flow meter or an online metering system that tests for methane, carbon dioxide, and hydrogen sulfide. If the facility does not have this equipment, operators can track electrical production (A). If production falls abruptly, it most likely indicates a change in composition of a substrate, though a number of other factors may also be the cause (E). If it is due to a compositional change in a substrate, having a strong relationship with the substrate provider is critical (E). A substrate provider may not want to be completely transparent about how their operation has changed (E). But if they understand that AD is a sensitive biochemical process, and that any slight change in the substrate can therefore have detrimental effects, they may be more willing to share information and help to find a solution. Ultimately, it is also in their interest to address problems and maintain the relationship for consistent waste disposal (E).

In addition to the effect substrate inconsistency can have on the digestion process, inconsistency can also negatively impact NMPs. Nutrient management plans are designed to apply nutrients (in this case found within the AD effluent) to crops at agronomic rates. To do this, effluent must be tested at appropriate intervals to determine nutrient content (A). If the nutrient content changes due to inconsistent substrate rates, or changes in substrate type, more testing is required, and the plan needs to be updated. Thus, consistent substrate composition and flow to the digester helps keep costs low for the farmer or project developer (A).

Industry Tip: Most food processing plants do not want to worry about finding new sources of waste disposal. When it leaves the plant, they want to know that there is a legitimate and legal place for it to go—and they value consistent working relationships.

Nutrient Concerns

At most dairy co-digestion projects, the impact of substrates on the dairy farm's NMP is a major concern (A, B, C, D, E). Most dairies manage the N, P, and K in manure or digester effluent by applying it to land, where the nutrients are utilized by crops (A, D). However, nutrients can have negative effects on water and air quality if over-application occurs. Because of this risk, many dairies and other CAFOs are tightly regulated regarding application of their wastewaters to soils (A, D).

AD does not degrade or destroy N and P, but rather converts it from organic to inorganic forms, which are more readily usable by plants. As a result, effluent includes most of the nutrients that were contained from AD inputs (A). When substrates are added to manure, the additional nutrients in the substrates may put dairies out of compliance with their NMPs. This is particularly true if the substrates are high in protein (N) or phospholipids (P), as is the case with many food-processing residuals (A). As one example, a study by Frear et al. (2011) showed that co-digestion of dairy manure with four different substrates (egg waste, fish breading, artificial crab meat, and ravioli sauce) increased the concentrations of total ammonia nitrogen (TAN), total Kjeldahl nitrogen (TKN), and total phosphorus (TP) (see Figure 6).

To better understand the nutrient management implications of a potential substrate, it is important to test nutrient content prior to introducing a new substrate to a digester (A, E). If the total nutrient load is increased in the effluent, NMPs may need to be adjusted. If nutrient overloading is a concern, NMPs may require effluent to be hauled to more distant fields to ensure that nutrient applications do not exceed the ability of plants to take up nutrients (A, D). When hauling is required, hauling costs may become a serious concern for a farmer. In this case, careful analysis is merited to understand whether or not these increased costs will be offset by the additional revenue generated from improved biogas production due to substrate addition (D). Another way to eliminate nutrient overloading and produce co-products is via nutrient recovery (A). Nutrient recovery is described in more detail in *The Rationale for Recovery of Phosphorus and Nitrogen from Dairy Manure* (Yorgey et al. 2014).

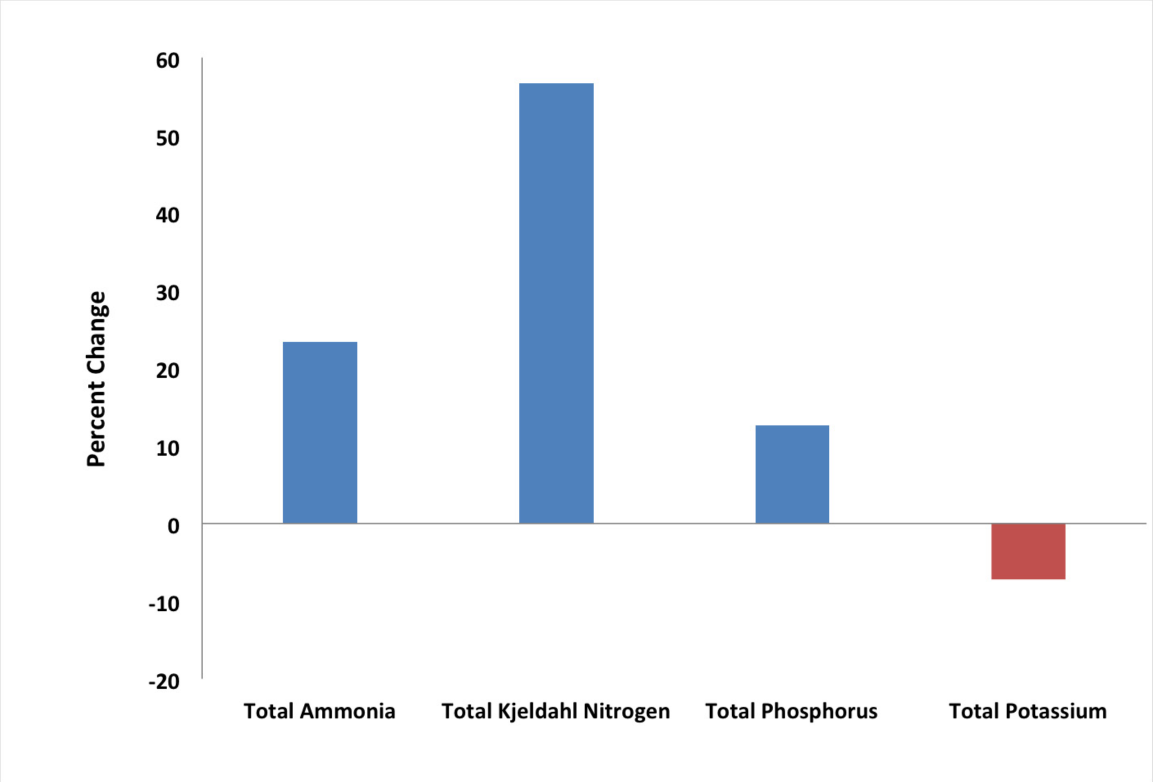

Figure 6: Percent change in nutrient content due to the addition of 16% substrates on a dairy in northwest WA. Graphic modified from Frear et al. 2011.

While dairy producers may be most concerned about total NPK loading and maintenance of an NMP, it is also important to understand the effects of co-digestion on changes in concentration and form of N (A, D). Dairymen with new digesters are often counseled to meet with experienced practitioners prior to their first field application, as modifications to their normal operating procedures are most likely needed to ensure crops are not burned due to the higher ratio of available N (ammonia). With changing substrate inflows, and therefore effluent nutrient concentrations, it is suggested that regular consultations with nutrient management experts be maintained to ensure crop yields and maintenance of a proper NMP (A).

As with all manure field applications, food safety is a concern. This concern is theoretically more problematic with co-digestion, particularly with certain meat processing and post-consumer substrates (A). To limit food safety concerns, some states, like Washington, have some degree of rulemaking on exemptions from standard solid waste management regulations. Refer to WAC 173-350-225 for more information.

Industry Tip: In some areas, the most important co-digestion consideration is how substrates will affect a dairy's farm plan and NMP. Substrates bring additional nutrients to the farm and a farmer needs to plan for properly disposing of these nutrients. If effluent hauling will be needed for proper disposal of additional nutrients, farmers should carefully analyze whether revenue increases will be sufficient to offset these costs, which can be significant.

Future Substrate Opportunities

As of 2014, most co-digestion projects in the U.S. either received substrates at no cost, or received a tipping fee. The availability of tipping fees is mostly a matter of location, with dairies located closer to more urban areas receiving tipping fees due to a localized higher need for organics diversion, relatively expensive landfill or other competing diversion costs, and limited alternative uses (A, B, E). In contrast, in more rural areas, organic wastes are more highly valued because they can be used as an animal feed, a notable competing disposal option (A). However, this landscape could change in the future, as indicated by the experience of the European AD market.

European countries that are heavily invested in AD are experiencing higher demand for substrates, to the point that some AD projects are paying for the right to receive substrates (De Vries et al. 2012).

In the U.S., as the food scrap and organics diversion movement continues to progress, only time will tell *if* and *when* co-digestion projects will need to pay for organics. With this future in mind, project developers have increasingly moved to business plans that do not rely on tipping fees to ensure project profitability (A, E).

Though the majority of digesters currently co-digest pre-consumer food wastes, interest is growing in AD of food scrap residuals and other municipal or industrial mixed wastes. From the perspective of digester developers and operators, these wastes represent an untapped source of substrates. Meanwhile, from a waste management perspective, AD could benefit organic waste recycling efforts. In the U.S., post-consumer food scraps are still the largest category (21.3% in 2011) of solid waste entering landfills, given existing recycling and composting efforts (EPA 2011). Similarly, in Washington and Oregon, 18% and nearly 17% of the total solid waste stream was food scraps, respectively (Ecology 2011; ODEQ 2009). While source reduction is the most sustainable way to reduce the amount of food scraps landfilled, a portion of this waste stream will still need to be recycled and diverted from landfills if a goal of zero landfilled organics is to be achieved.

In the U.S., most post-consumer food scrap recycling is currently achieved via composting. For example, in western Washington, many residents of Seattle and King County have their food scraps recycled along with yard waste into saleable compost (A). While this effectively diverts food scraps from landfilling, AD could capture the energy within food scraps and use it to replace fossil-derived energy, providing additional benefits. When linked with nutrient recovery, the process could also produce saleable fertilizers (A). If dairy farmers are located near post-consumer food scrap sources, they may be able to position themselves well as an environmentally conscious (lower odor production, greater energy benefit derived) and less expensive (shorter hauling distances and lower tipping fees) recycling option (A).

Existing barriers to co-digestion of post-consumer food wastes include current regulations excluding these wastes from AD, and the extensive pretreatment required so that these wastes could be viably fed to digesters (A). However, if solutions to these issues could be found, it could be a win-win scenario for food waste diversion and AD projects looking to remain viable.

Conclusion

Co-digestion can provide a significant economic boost to AD operations at dairies. However, interviews with experts in the field of co-digestion make it clear that careful consideration and planning is required to successfully incorporate substrates. Substrates should be chosen to complement existing waste streams, and should be carefully screened to avoid inhibition.

In most cases, the selection of a substrate will be limited by location and volume attainable, and project developers may need to invest considerable time and effort into developing and maintaining the necessary relationships for acquiring substrates. Regulatory restrictions and nutrient management implications are also important. A solid understanding of these issues can contribute to successful implementation of co-digestion.

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