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Anaerobic Digestion of Food Waste: Products and Their Uses

Introduction

Anaerobic digestion (AD) is a relatively simple biologically mediated, thermodynamically driven carbon management process carried out in the absence of oxygen. A self-establishing consortium of bacteria comprising hydrolyzers, acidogens, acetogens, and methanogens convert complex organic compounds into simpler molecules (hydrolyzers), simple molecules into volatile fatty acids (VFAs) (acidogens), VFAs into acetic acid (acetogens), and acetic acid into biogas (methanogens) to derive energy and metabolic building blocks. In contrast to aerobic digestion, which converts organic waste primarily to microbial biomass and carbon dioxide (CO_2), AD generates mainly methane and digestate. Typically, AD is used to treat large volumes of diverse, high-strength organic waste, as it is less capital intensive, has lower operating costs, and takes up less space than a comparable aerobic system.

At steady state, the outputs from traditional AD units are biogas and digestate. The biogas is primarily made up of methane (CH_4) and CO_2, with traces of hydrogen (H_2) and/or hydrogen sulfide (H_2S). These gases leaving the system "pull" the remaining complex molecule conversions through the consortial metabolism of converting complex organic compounds to biogas. If the methanogens that convert the acetate to biogas are inhibited, the acetate and VFAs build up and "sour" the digester by stopping the consortium from functioning. This is a primary concern for AD of food waste, as methanogens are particularly sensitive to low pH, which can be caused if high VFA production rates from acidogens and acetogens (using easy-to-digest compounds found in food waste) exceed the methanogenesis rate. Food waste often has high protein levels as well, and ammonia production during proteolysis can also inhibit the methanogens. The key to a functional digester is keeping the methanogens happy.

The feed rate into the system is equal to the output rate of biogas plus the digestate (solids plus liquor or "centrate"). The solids are composed of undigested feed material and the microbial biomass produced. The liquor contains water plus any soluble organic compounds and salts. When the digestate results from anaerobic digestion of sewage, the solids are referred to as biosolids. The fraction of input solids converted is typically between 40%–60% and is dependent on many factors such as solids retention time, feedstock composition, digester configuration, and digester operating conditions. Many AD operations use chemical oxygen demand as a metric to determine the extent of digestion. Although chemical oxygen demand is simple and easy to measure, it was originally developed as a measure of water quality and tells you nothing about the composition of the organic compounds in the sample. This may be enough for the purposes of the U.S.

Note: Research into anaerobic digestion of food waste, especially on uses for digestate, is limited in comparison to sewage and manure. However, there is little reason that technologies developed for these large-volume feedstocks cannot be applied to food waste digestate in many cases. This summary includes sewage-based biosolids conversion methods where they could be applicable to food waste digestate.

Environmental Protection Agency, but it provides no detailed information about which components are converted or which remain in the digestate. Because the value of the digestate is often determined by its composition, more detailed chemical analyses are required. However, there is no current standard by which this can be measured, as discussed in the following sections.

Biogas

The major market product from anaerobic digestion is biogas, specifically the CH_4 fraction. Typically, CH_4 makes up about 60% of the biogas, ±10%, with CO_2 comprising most of the remainder. The key use of CH_4 is as an energy source to produce heat, electricity, and renewable natural gas that could be injected into the pipeline system or used as a transportation fuel. As such, it needs to be cleaned up and upgraded in most cases. CO_2 needs to be removed to increase the thermal value and decrease emissions. This is often done by water stripping or pressure swing adsorption. H_2O, H_2, H_2S, and some nitrogen compounds are usually found at low levels in biogas. H_2O lowers the heating value and causes corrosion issues. H_2S is toxic and corrosive and must be mitigated in most cases, usually by adding in air/O_2 to oxidize it or reacting with an iron compound to convert it to less-toxic iron sulfide and H_2. Another consideration is that increasing the amount of biogas produced not only increases the methane, but it also reduces the amount of biosolids. Basically, every kilogram of biogas made is one less kilogram of biosolids that requires disposal or other use.

Increasing the CH_4 fraction of biogas can improve the economics by providing more product and reducing cleanup costs. Thermophilic AD has been shown to increase CH_4 production.[1] Balancing feedstock inputs using co-digestion strategies can increase CH_4 production, as can developing better consortia.[2-7] Feedstock pretreatment can also be used to increase both CH_4 production and feedstock utilization. Thermal, chemical, thermochemical, mechanical processing, enzyme, and other preprocessing of the feedstock has been shown to increase CH_4 production and the rate and extent of conversion of multiple feedstocks.[1, 8-14]

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What to do with the CO_2 is another consideration. Around 30%–40% of the biogas is typically CO_2. It is low value and limited in use—for example, it cannot be used in food processing. Certain microbes can convert it to methane if given enough H_2. Recent advances in this area made by the National Renewable Energy Laboratory have demonstrated the efficient conversion of biogas CO_2 to methane using a pressurized microbial bioreactor fed with biogas and H_2 produced by electrolysis of water.[15] Using renewable electricity to produce the H_2 makes this process 100% renewable, and it can be bolted on to any biogas system. Alternatively, the CO_2 could be a good candidate for carbon sequestration, as this CO_2 is organically derived and is a concentrated point source of carbon. It has even been suggested that the CO_2 could be used to grow algae to facilitate nutrient removal from AD centrate and generate bioproducts from the algae.[16]

Digestate

Anaerobic digestate is the combined liquid and solid fractions left after the AD process. The solids fraction comprises undigested feedstock and microbial biomass produced as a result of growth in the digester. Typically, the inorganic content is the same as the feedstock (i.e., same potassium, phosphorous, and nitrogen levels), as most of the mass loss is from organic (i.e., carbon) degradation. The chemical composition varies, primarily as a function of the feedstock and digestion parameters, but it often contains high fractions of cellulose, lignin, and some protein. Due to the retained nutrient value, it is most often used as a fertilizer, though application is restricted in certain areas. Additional pressures limiting landfilling of organics in many areas are also driving the need for additional outlets for digestate. Due to the large volume of sewage treatment, there has been a great amount of research on conversion of biosolids to products. Similar efforts in food waste digestate have lagged but are increasing with the recent emphasis on diversion away from landfills and limits on land application due to nutrient and heavy metal buildup in soils. The current options for food waste digestate are diagrammed in Figure 1 and detailed in the following sections.

Solid-Liquid Separation

The solid-liquid ratio of AD feed streams is highly dependent on the source and has a large impact on the digester design, operation, and handling costs. In general, AD can be characterized as "wet" (<10% total solids), "semi-dry" (10%–15% total solids), or "dry" (>15% total solids).[17] Higher total solids can be handled in smaller digesters with lower capital costs, and low moisture content in the digestate means lower volume to

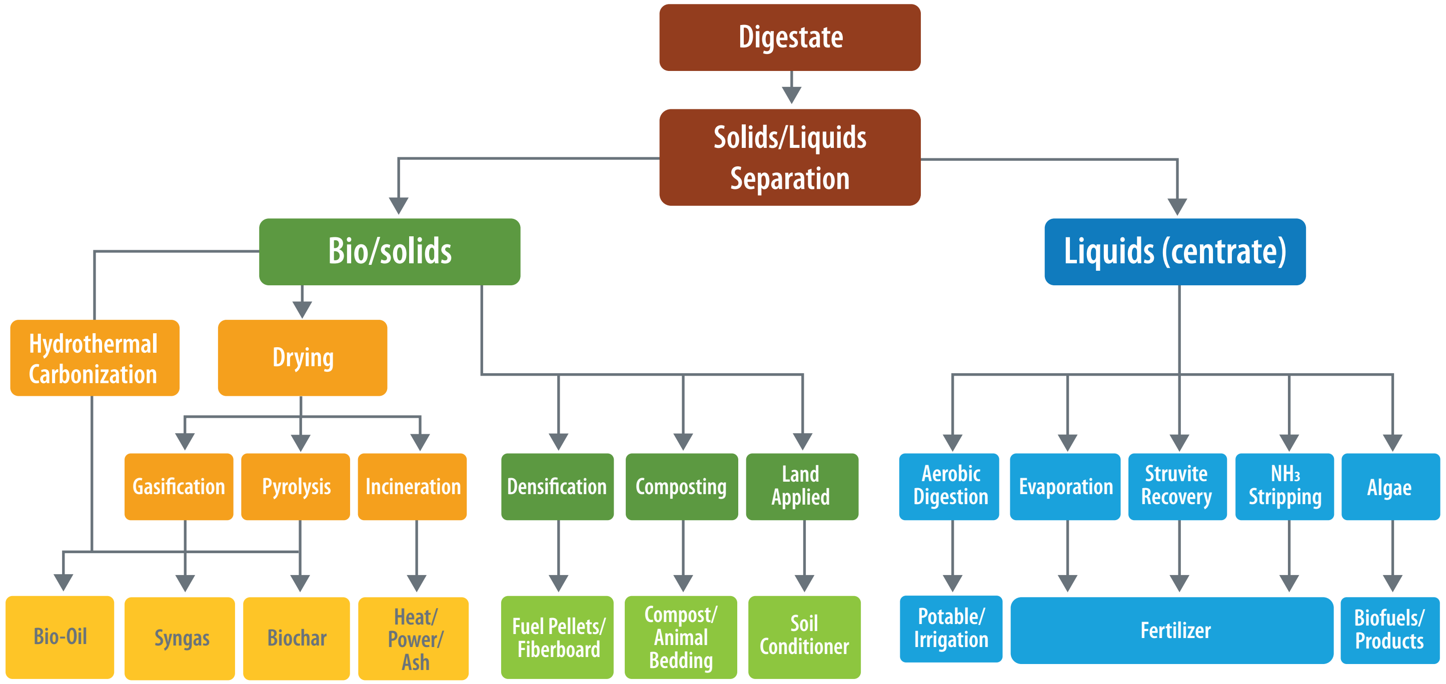

Figure 1. Current and potential uses for food waste digestate

transport and process. On the other hand, mixing is easier with higher water content, and pumps can be used to move the components around. Higher water content also provides for lower concentrations of VFAs and ammonium compared to high solids, providing better conditions for methanogens.

Adjusting the solid-liquid ratio often requires a solid-liquid separation—or dewatering—step. This dewatering, or thickening as it is often called, is a major unit operation at many AD plants, and numerous companies and methods are available to facilitate this effort. Settling, microbial or chemical flocculation and/or coagulation, centrifugation, chemo- or electro-oxidation, acidification, air drying, hydrothermal treatment, ultrasound, electrochemical precipitation, pressing, and filtration have all been studied or employed in AD solid-liquid separation.[18-30] Recent studies using biochar as an AD additive have demonstrated positive benefits in both methane production and dewatering parameters, though the impact of the biochar on the digestate end use should be considered.

Land Application

The most common use for digestate is land application. It typically has high fertilizer value, and the organic content is useful in restoring lands where topsoil has been removed, such as mining sites and deforested lands. Smaller-scale applications include compost, home and garden fertilizer, landscaping mulch, and even as eco-friendly decomposable planters. For example, Bloom is a commercial mulch derived from a water treatment plant in Washington, D.C.[31] It is available in bulk for commercial and agricultural use, dried and packaged for home and small business, and blended with woody biomass or sand for specific applications.

Digestate solids from food waste are processed similarly. The primary limitation to land application is transportation cost. Digestate is expensive to transport and apply, so land application is typically carried out close to the site of production. As a result, the land immediately surrounding an AD plant rapidly becomes saturated with nutrients, and regulatory limits restrict further application. Eventually, longer distances preclude economic transport and other uses of the digestate need to be developed.

Depending on the soluble compounds present, the centrate can be processed to generate fertilizer (from high phosphorus and nitrogen containing systems). The concentration and processing has been demonstrated to consume approximately 10% of the total energy produced by the digester[32] using evaporation and reverse osmosis processing. This can be combined with specific nutrient removal via ammonia stripping and struvite precipitation to generate nitrogen-balanced fertilizers. Because phosphorus is a major component in many AD centrate streams, there is high interest in recovering this diminishing resource for multiple reasons. Removing phosphorus can mitigate operational issues with struvite formation in pipes and tankage. Also, because many digestate-treated lands are becoming overloaded with phosphorus, removing it could allow continued application in nearby lands. Lastly, concentrated phosphorus can be used in fertilizer and transported to distant areas that are phosphorus-deplete.

Direct Fuel

Biosolids from sewage have been heavily researched and developed for use as fuels due to their ever-increasing volume and broad availability. Although little work has been done on

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food waste digestate in this area, there is little reason to think it would not be just as suitable. One recent study looked at co-combusting with municipal solid waste, and although the food waste digestate had a lower energy content, blending with municipal solid waste mitigated this to some extent and was still feasible.[33] Biosolids, and potentially food waste digestate, can be used as fuel in multiple ways. After drying, the biosolids can be burned directly, usually in a fluidized bed incinerator, generating both heat and potentially power. In Europe, electricity generation from this can command higher prices due to the "green" status of the production. The additional advantage is that the solids volume is greatly reduced, with stabilized inorganic ash being primarily the only residue created. The downside is that emissions require mitigation, and some of the energy recovered is required to dry the material before burning it. Similar to incineration, co-firing of biosolids in existing coal- or biomass-fed power plants provides power from the digestate and takes advantage of existing combustion, generation, and emission control infrastructure.[34] A potentially major outlet for biosolids is co-firing in cement kilns. This is currently used in Europe and presents the advantages of (1) disposing biosolids, (2) displacing fossil fuels used in cement manufacturing, and (3) incorporating the resultant ash into cement.[35]

Fuel pellets made from drying and forming biosolids and co-fired with coal or wood pellets have been researched and proposed for years, but commercial adoption has lagged.[36-38] Multiple studies have reported that co-firing with more traditional fuels demonstrates no issues, but commercial implementation has not been carried out on any great scale.[39] A major obstacle is the high cost of solid-liquid separation needed to produce dry pellets. Small AD operations are limited in their ability to economically produce these pellets due to their low production volume; however, large municipal facilities or combined small-scale operations are likely to reduce this cost considerably into the economical range.[38] An advantage of this process is that phosphorus can be sequestered into the pellets instead of being discharged with the spent centrate. Not only does this remove and concentrate the phosphorus, but it has also been shown to eliminate pathogens such as Clostridium spp.[40] When burned, the resultant high-phosphorous ash can be used in fertilizer production.[38] Though not specifically related to fuel applications, digestate pellets could also be used as soil amendment; however, it has been shown that digestate pellets produce significant N_2O emissions when applied on soils.[41] Recently, several companies have begun to market digestate pelleting operations and equipment for both fuel and fertilizer pellets (e.g., Elf Systems, Nawrocki Pelleting Technology, and Kesir).[42–44]

Indirect Fuel and Products

High-strength centrate has been used to stimulate algae growth in treatment ponds, where the algae clean the water by removing nutrients (mainly nitrogen and phosphorous) and the algae are subsequently processed to produce biofuels or bioproducts.[45–47] Recent interest in diverting carbon away from biogas and toward liquid fuels and products is leaning towards production of VFAs and/or longer-chain alcohols by arresting methanogenesis. In this process, the methanogens are inhibited chemically, thermally, or physiologically (low/high pH), and VFAs are allowed to build up in the centrate. Separating the VFAs from the centrate using mechanical, physical, electrochemical, or other means mimics the methanogenesis and allows the hydrolysis, acidogenesis, and acetogenesis to continue while providing a higher-value stream of VFAs to serve as feedstock chemicals for catalytic or biological upgrading to hydrocarbon fuels, higher alcohols, or other bioproducts. This work is still preliminary, but it holds much promise for valorizing AD operations beyond just methane.

Water

The centrate, or liquid fraction, of the digestate contains both soluble compounds and water. Aerobic water treatment is often used to biologically "combust" the soluble organics in low-strength wastewater to CO_2. Combined with settling/filtration and other treatment steps, both potable and irrigation water can be produced. Likewise, the centrate can also be recycled back into the AD process to provide process water if needed.

Bio-Oil, Biochar, and Syngas

Biosolids can be transformed into liquid and gaseous fuels using thermal or thermocatalytic processing. Pyrolysis, gasification, and hydrothermal liquefaction are all proposed routes to convert biosolids to such products, but pyrolysis is a bit behind in the technology development. The technology readiness levels for pyrolysis, gasification, and hydrothermal liquefaction are 5, 6–7, and 6, respectively. The primary differences between these technologies are in the parameters used (moisture, temperature, and pressure), which determine the products formed, the fraction of each, and extent of conversion.

Gasification (>800°C, some O_2 present) generally produces syngas (CO and H_2), as well as tar—a major problematic byproduct. The biosolids must also be dried first. At least one gasification demonstration facility has been in operation in Tokyo since 2010.[48] Pyrolysis (400°C–600°C, no O_2) produces mainly H_2, CO, CO_2, CH_4, bio-oil, and char. Pyrolysis requires low moisture, mid-temperatures, and lower pressures compared to hydrothermal liquefaction, which has lower temperatures but higher pressure and can handle large amounts of water.

Thermo-catalytic reforming[49] and hydrothermal processing are thermal processes that convert organic waste into several fuel-type product streams—primarily bio-oil (bio-crude), syngas, and H_2. Biochar or hydrochar is also produced and can be used as a soil conditioner/fertilizer and carbon sequestration mechanism.[50, 51] Biochar has been shown to increase methane production in high-solid digesters by fostering microbial interaction and increasing the fractional methane content by adsorbing CO_2.[17, 52] As a soil conditioner, biochar can provide slow release of phosphorus and help sequester nitrogen.[53, 54] Lastly, multiple studies have examined the use of biochar to adsorb metals, nutrients, and contaminants from digestate.[55–60] The thermo-catalytic reforming process being developed by the European Union in its TO-SYN-FUEL project uses dried biosolids as a feedstock, but food waste digestate should be amenable as well. The primary products of thermo-catalytic reforming are syngas, bio-oil, and H_2.[49] Over a pyrolysis temperature range, food waste pyrolysis has been shown to produce the typical yields of bio-oil (17% at 400°C to 23% at 700°C), biochar (64% at 400°C down to 52% at 700°C), and syngas (18% at 400°C to 25% at 700°C).[61]

Hydrothermal processing handles wet organic material, as water is part of the reaction, and can be divided into hydrothermal liquefaction (200°C–400°C) and hydrothermal carbonization (180°C–250°C). Hydrothermal liquefaction produces bio-oil, syngas, and biochar, whereas hydrothermal carbonization produces mostly CO_2 and hydrochar.[62] For any of these processes, the syngas can be burned directly or used to make fuels like diesel. Bio-oil can also be burned in heavy engines or refined into diesel, jet, and gasoline-like fuels. Bio-oil generally requires cleanup and processing before use and is not optimal for standard internal combustion engines, though this can be addressed by different engine designs. Water recovered from either process can be reprocessed at the water resource recovery facility or fed back into the digester. Currently, this technology is being applied to biosolids, though food waste digestate would serve as well.

One other interesting approach is to combine produced syngas with the AD step. The CO_2 and H_2 in the syngas can be reformed into CH_4 in the digester, increasing CH_4 yields and titers.[61]

Other Uses

After dewatering and drying, digestate is often used for animal bedding.[63] Although this is a low-cost and mostly local outlet, the bedding often ends up back in a digester, thus increasing the ultimate extent of conversion of the original food waste. Other examples include using food waste digestate to grow edible mushrooms, as published by one clever graduate student,[63] or as a nutrient source to grow

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algae for biofuel production,[64] similar to other liquid digestates. Research at Michigan State University indicates that medium-density fiberboard and fiber-plastic composites can also be manufactured successfully from digestate solids.[65]

Takeaways

The main utilization options for food waste digestate currently revolve around land application or animal bedding. There are some demonstration technologies in place or being built to evaluate thermal conversion of biosolids to fuels and biochar, and several companies are promoting these options, but they are not yet fully commercialized, and research needs to be done to validate that food waste will perform similarly to biosolids. Several companies have proposed pelletizing biosolids for use as a co-fuel with wood pellets, and although food waste digestate could be just as effective, there are no commercial or even pilot operations at the moment. Part of the lack of information and demonstration is the relatively low level of food waste digestion operations compared to sewage and manure. As food waste becomes a larger fraction of AD feedstocks in both stand-alone and co-digestion facilities, operators will need to test these various technologies to empirically determine their utility and economics.

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