OPEN ACCESS

Advances in Food Processing and Technology

Wilson RT. Adv Food Process Technol: AFPT-115.

Brief Report

DOI: 10.29011/AFPT-115. 100015

Anaerobic Digestion of Food Waste for Bioenergy Production

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Citation: Xu F, Li Y, Wicks M, Li Y, Keener H (2018) Anaerobic Digestion of Food Waste for Bioenergy Production. Adv Food Process Technol: AFPT-112. DOI: 10.29011/AFPT-112. 100012

Received Date: 11 July, 2018; **Accepted Date:** 30 July, 2018; **Published Date:** 03 August, 2018

Abstract

The disposal of large amounts of food waste has been a significant environmental problem and financial burden globally. Compared with traditional disposal methods (i.e., landfilling, incineration, and composting), Anaerobic Digestion (AD) is a promising technology for food waste management. This article describes the fundamentals of AD, including its basic biological processes and important operating parameters, such as nutrient requirements, temperature, and total solids content. The application of AD of food waste is also discussed, including food waste mono-digestion and co-digestion with agricultural waste and sewage sludge. AD of food waste was concluded to be a promising technology, but there are still many technical, economic, and social challenges for the mono-digestion of food waste. Currently, co-digestion is a viable option that is widely applied.

Keywords: Agricultural Waste; Anaerobic Digestion; Bioenergy; Biofuel; Biogas Food Waste; Co-Digestion; Digestate; Methane; Operating Parameters; Sewage Sludge; Waste Management; Waste Recycle

Synopsis

This article starts with the global challenge of the generation and disposal of large amounts of food waste, and how Anaerobic Digestion (AD) can serve as a promising approach to convert food waste to renewable energy and fertilizers. Then, the fundamental knowledge of AD, including its basic biological processes and important operating parameters is explained, followed by the application of AD for food waste. Finally, AD of food waste is concluded to be a promising technology, but there are still many technical, economic, and social challenges for its wide application.

Problem with Food Waste Generation and Recycle

The increasing generation and disposal of food waste have been causing tremendous social, environmental, and economic problems [1-3]. Since 1974, the amount of food waste in the U.S. has increased by 50% [4], and in 2014, about 38 million tons of food waste was discarded, composing about 40% of the organic fraction of municipal solid waste disposed [5]. Globally, one third (about 1.3 billion tons) of the world food production is lost or wasted in the food supply chain, including during production, processing, distribution, storage, retail, preparation, cooking, and serving of food [6].

Food waste from the production and processing stages usually have high potential to be further processed to produce animal feed, chemicals, and fuels. In developed countries such as Japan and the U.S., it was reported that up to 95% of food processing waste has been recycled for beneficial use, resulting in a low disposal rate of only 4-5%; while the spoiled food from retail stores has a lower recycling rate of about 37-42% [6-8]. Food waste generated from the consumer end, such as restaurants, beverage shops, homes, school, and hospitals, although estimated to be potentially 90% recyclable, has the lowest recycling rate of only 15-17%, due to its complex composition, various impurities, and a lack of disposal restrictions [6-8]. Developing countries tend to lose more food in the early stage of the food supply chain due to the limited technology implementation in harvesting, transportation, and storage, which accounts for about 80-90% of their total food loss [2]. Worldwide, 40% of the food loss and wastage happens at the retail and consumer stages (about 222 million ton in total), which is almost as high as the total net food production in sub-Saharan Africa (230 million ton) [2].

The desired food waste recovery hierarchy proposed by the U.S. Environmental Protection Agency (USEPA) is shown in Figure 1. Reducing food wastage from the source of generation is the most favorable option. Some high-quality food can be donated to food banks to feed people in need, but hygiene concerns and transportation costs have to be addressed. For unrecycled food waste, landfilling and incineration are the least favorable treatment methods due to their negative environmental impacts and the losses of energy and nutrients. Composting is the second last favored option as it does not recover the process energy, and is also not suitable for liquid food waste such as food processing wastewater [4,9]. If the food waste cannot be diverted to human or animal feeding, industry uses are the preferred method. Examples include using waste cooking oil to produce fuel, or using food waste in Anaerobic Digestion (AD) to recover energy and nutrients [10,11]. Among all these options, AD might be the most adaptable method as it can be used for all types of food waste, regardless of the quality, water content, or other restrictions.

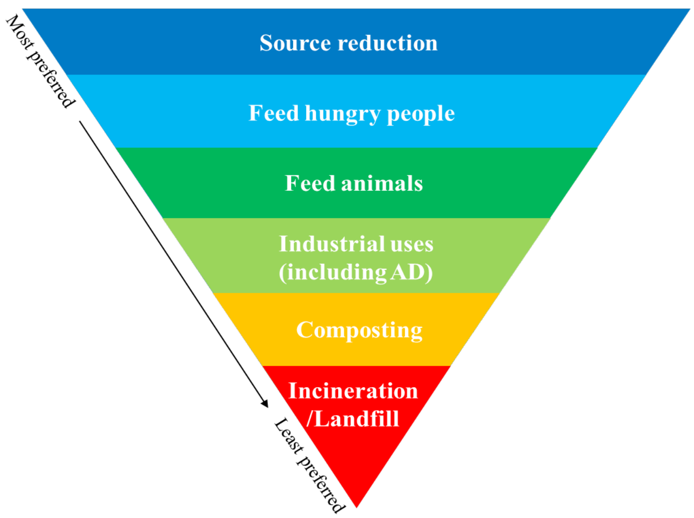

Figure 1: The food recovery hierarchy proposed by U.S. Environmental Protection Agency (EPA). Adapted from [5].

AD Fundamentals

Biological Processes

AD is a microbial process in which organic matter, such as food waste, animal manure, and sewage sludge, is decomposed in an oxygen-free environment by anaerobic microorganisms. One attractive feature of AD is that both of the two major products from the process can be beneficially used. The first one is a gaseous stream called biogas, which is a mixture of primarily methane (50%-70%) and carbon dioxide (30-50%), and can be burned to generate heat and electricity or be cleaned and purified so that the methane can be injected into natural gas pipelines or be compressed to produce vehicle fuels. The typical composition of biogas is shown in Table 1. The second stream is a liquid (effluent) or solid residue (digestate) that consists of nutrients (N, P, K, and micronutrients), water (range from 70-99%), and stabilized organic matter, which can be used as a fertilizer or soil amendment [12,13]. Compared to many other bioenergy technologies, AD can accommodate a much wider range of substrates and can be conducted in both large and small scale digesters and at most geographical locations [14].

Component	Content
Methane (CH_4)	53-70%
Carbon dioxide (CO_2)	35-50%
Nitrogen (N_2)	<6%
Oxygen (O_2)	<5%
Hydrogen (H_2)	<1 %
Hydrogen sulfide (H_2S)	<2000 ppm
Organic compounds and other impurities	Trace amount

Table 1: Typical composition of biogas. Adapted from [15].

Food waste, as well as other organic matter, decomposes in AD in a series of steps (Figure 2) by different types of microbes. Complex organic matter is composed of different percentages of carbohydrates, proteins, and fats. Anaerobic microbes decompose these compounds into simpler, more soluble organic compounds such as sugars, amino acids, and fatty acids, uptake them into cells, and further ferment them step by step into simple compounds like acetic acid, H_2, and CO_2. Acetic acid, H_2, and CO_2 can be directly taken up by methanogenic microbes to produce methane.

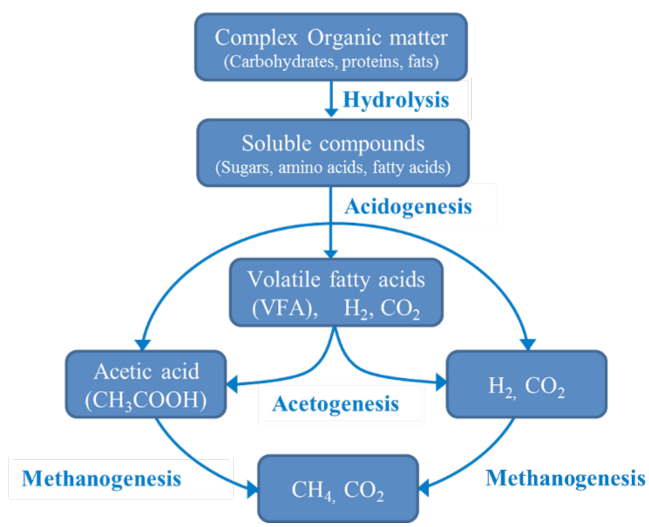

Figure 2: Process of organic matter decomposition during AD.

The theoretical reaction stoichiometry of AD of different organic matter can be written using the Bushwell equation, in which C, H, O, N and S are converted into CH_4, CO_2, NH_3 and H_2S [16]:

$$C_nH_aO_bN_cS_d + \left(n - \frac{a}{4} - \frac{b}{2} + \frac{7}{4}c + \frac{d}{2}\right)H_2O \longrightarrow \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4} - \frac{3}{8}c - \frac{d}{4}\right)CH_4 + \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4} - \frac{5}{8}c + \frac{d}{4}\right)CO_2 + cNH_4HCH_3 + dH_2S$$

Therefore, ideally, the methane yield from different substrates can be estimated using their elementary composition. In reality, however, organic materials have a complex structure and usually do not completely decompose during AD. The actual methane yield of different substrates depends on many factors, such as whether or not the material structure is easily decomposable by microbes, the nutrient composition of the substrates and AD operating parameters are suitable for microbial growth, and different groups of microbes are well balanced so that no inhibitory intermediate products, such as VFAs and H_2, are accumulated.

The theoretical CH_4 yields and contents of some common model substrates are shown in Table 2. Lipids have the highest theoretical methane yield because of the low content of O and relatively high contents of C and H. It has also been observed that lipids-rich materials, such as kitchen food waste and FOG (Fat, Oil, and Grease) can boost methane production from AD. However, excess lipids in a digester will cause accumulation of long-chain fatty acids, which are inhibitory to methanogenic microbes and can cause digester failure [17].

Substrate	Typical chemical formula	CH_4 yield (STP m^3/kg)	CH_4 (%)
Cellulose and starch	$(C_6H_{10}O_5)_n$	0.415	50
Hemicellulose	$(C_5H_8O_4)_n$	0.424	50
Protein (cellular)	$C_5H_7NO_2$	0.496	50
Lipids (triolein)	$C_{57}H_{104}O_6$	1.014	70

Table 2: Theoretical methane yields and contents of model substrates [18].

Important Operating Parameters

Management of an AD system is important to ensure the balance of nutrients, the production and consumption of organic acids, and a stable operating condition. Otherwise, the digester will be acidified and fail, requiring cleanout. Some important parameters that affect the success and rate of AD process are introduced in this section.

Nutrient Requirements: Like most of the biological process, microbes in AD need macro- and micronutrients (e.g., nitrogen, phosphorus, and trace elements) to produce new microbial cells and important enzymes. The carbon-to-nitrogen (C/N) ratio is one of the most commonly used parameters to estimate the balance of nutrients in AD. Microbes use carbon as the energy source and nitrogen mainly for protein production. Based on lab studies, the recommended C/N ratio for microbial growth for AD is 20-30, with 25 being the optimal. However, many studies have shown that AD processes are still "healthy" with very low or high C/N ratios such as below 15 or above 40. It is likely that the feeding formula for AD can have a high variability, like the human diet, and the availability of carbon and nitrogen during degradation, as well as the acclimation of the microbial community, affect the threshold of C/N ratios.

In addition to nitrogen and phosphorus, some micronutrients are also essential for anaerobic microbes, such as iron (Fe), nickel (Ni), cobalt (Co), molybdenum (Mo), selenium (Se), calcium (Ca), magnesium (Mg), zinc (Zn), copper (Cu), manganese (Mn), tungsten (W), and boron (B) [19]. Lacking these essential nutrients affects the functions and activities of key enzymes and change the environmental conditions, such as oxidative-reductive potential, for microbial growth [10], resulting in digester failure. Food and kitchen waste generally contain low concentrations of trace elements. Addition of animal manure or sewage sludge is a widely used solution to provide sufficient micro-nutrients. However, in some cases food waste is used as the sole substrate, and supplementation of micronutrients is necessary to prevent digester failure.

Temperature: The reaction rate of AD, like most other biological processes, is strongly dependent on temperature. Usually, biological activity doubles for every 10˚C increase in temperature within the optimal temperature range. The growth rate and activity of anaerobic microbes generally follow the same trend. However, the type of methanogens and other bacteria shift with temperature, thus there exist three optimal temperature ranges, which correspond to different dominant species of methanogens, as shown in Figure 3 and described below.

- **Psychrophilic:** 10-20˚C. This type of digester is usually simple and operated at ambient temperatures, such as covered manure storage lagoons and small-scale home digesters. Biogas production is low and varies significantly with the temperature of the digester.
- **Mesophilic:** 35-40˚C. This is the most commonly used temperature for commercial large scale digesters. Heating is often required but can be provided by combustion of biogas or by hot water from combined heat and power generation systems. AD is usually easy to control under this temperature and also has higher net energy production [20].

- **Thermophilic:** 50-60°C. Anaerobic microbes have the highest activity and growth rate at this temperature, and thermophilic digestion also leads to pathogen destruction. However, the thermophilic microbial community has lower diversity and high sensitivity to fluctuations of environmental conditions such as temperature and pH, causing digesters to be less stable. Another concern about thermophilic AD is the potentially high energy input for heating, which may offset its higher methane production yields and rates, causing a lower net energy production than mesophilic temperatures [20]. However, thermophilic AD has been proposed to be favorable for food waste digestion because the high methanogenic activity can rapidly consume VFAs and prevent a pH drop.

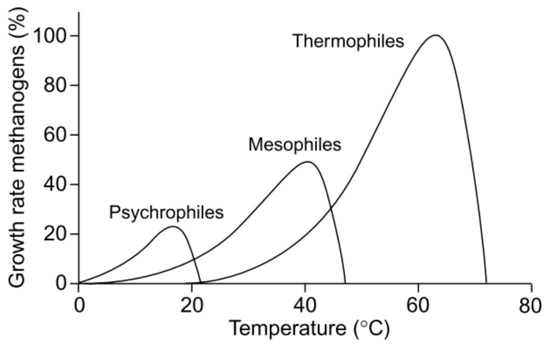

Figure 3: Relative growth rate of psychrophilic, mesophilic, and thermophilic methanogens. Adapted from [21].

Total Solids Content

The operating Total Solids (TS) content is an important parameter in AD. A high TS content is preferred because excessive water in the digester occupies effective volume, consumes energy for heating, and generates large volumes of wastewater. However, high TS contents reduce the reaction rate and methane yield (methane produced per unit of substrate), thus offsetting the benefits of adopting it. Xu F, et al. [22] found that the maximum volumetric methane production rate of AD first increased with TS, reaching a maximum value at 15%-20% TS, and then started to decrease (Figure 4). Fernández et al. [23] also reported a 17% decrease in organic waste degradation when the TS content increased from 20% to 30%. Based on TS content, AD systems can be divided into liquid AD (operating TS < 15%) and solid-state AD (operating TS unusually above 20%). In practice, the selection of the operating TS is usually determined by the substrate that is added to the digester. For example, L-AD is usually fed with liquid and pumpable organic wastes, such as manure, sewage sludge, or food waste processing water, and the digesters are usually tanks with mechanical mixing. In contrast, SS-AD is commonly fed with solid organic wastes such as the organic fraction of municipal solid waste, crop silage, and solid food waste, and operates similar to a composting in sealed vessels. L-AD is currently more common, and one of its most important parameters is the Organic Loading Rate (OLR) which indicates how much organic waste is added per digester volume per unit time. Increasing OLR is preferred, while if the OLR is too high, the degradation efficiency of organic waste maybe compromised and the microbes might be overloaded which may cause digester failure.

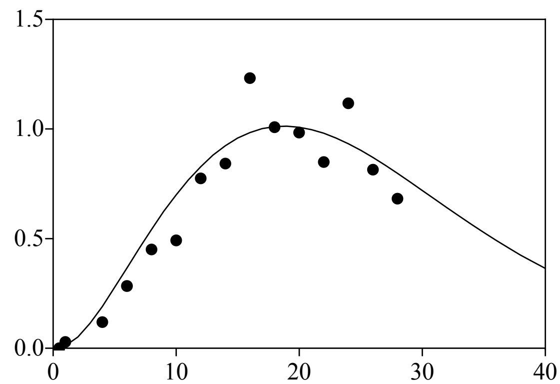

Figure 4: Effect of TS content on the maximum methane production rate [22]. Dots are experimental values and the line is a model simulation.

Applications of AD of Food Waste

Traditionally, AD has been more widely used in the treatment of high-strength wastewater, sewage sludge, and animal manure. In contrast, AD has not been used for food waste due to technical, economic, and social problems, such as its high variability and degradability which are hard to control, and the lack of government regulations to divert it from landfills. In the U.S., less than 2% of food waste is anaerobically digested, much less than the amount that is composted or landfilled [6]. However, in recent years, food waste has become an increasingly popular AD substrate due to its high energy content, large quantity, and wide availability [9,24].

Mono-Digestion of Food Waste

The characteristics and methane yield of some common food wastes, including industrial food processing waste, food processing wastewater, and kitchen food waste, are summarized in Table 3. The TS content of food waste has a wide range from a dilute liquid (less than 1%) to high-solid (30-90%). The characteristics of the same category of food waste can also be highly variable, due to differences in sources, processing and handling methods, eating habits, culture, climate, and seasons. For example, fruit and vegetable residues can vary with seasons, and kitchen food waste from different countries also varies significantly. AD processes have to be designed and adjusted according to the characteristics of the food waste to obtain optimal treatment efficiency. As discussed in section 2.1, the methane yield from food waste is affected by the contents of carbohydrates, proteins, and lipids. In Table 3, FOG and dairy waste achieved the highest methane yields due to their high lipids content. In contrast, brewery, vegetable, and fruit wastes contain more fiber and have lower methane yields. However, the methane yield of a certain substrate has a wide range depending upon its composition and AD operating parameters; when AD conditions are not favorable, substrates cannot achieve their maximum potential.

Food and food processing wastes	Components	TS%	C/N ratio	Methane yield($m^3/kgVS_{feed}$)
Fat, Oil and Grease (FOG)	Produced at food service or other food preparation facilities	1.3-3.2	22.1	0.4-1.1
Dairy industry wastewater	Water, milk solids, detergents, sanitizers, milk wastes etc.	0.1-7	11.4-13.6	0.1-0.85
Household and restaurant food waste	Nonedible portions of food (e.g. banana peels, egg shells) and uneaten food such as plate waste.	4.0-41.5	11.4-36.4	0.46-0.53
Slaughter-house waste	Blood, manure, hair, fat, feathers and bones.	2.0-28.3	43254	0.20-0.50
Waste pet food	Smashed meat, starch, dietary fiber.	86-93	45931	0.15-0.50
Fruit and vegetable waste	Leaves, peels, pomace, skins, rinds, cores, pits, pulp, stems, seeds, twigs, and spoiled fruits and vegetables.	7.4-17.9	15.2-18.9	0.16-0.35
Brewery waste	Spent brewer's grain, yeast, hops and trub (proteins), diatomaceous earth slurry from beer filtration.	23.0-29.2	18.8-54.9	0.22-0.31

Table 3: Methane yields of some common food waste and food processing waste. Adapted from [19].

Mono-digestion of food processing wastewater has been widely used in the food industry to treat high strength wastewater [24]. However, mono-digestion of high-solids and more complex domestic food waste, such as those from homes, restaurants, schools, and hospitals, has not been widely applied. The major technical challenge is that food waste is generally rich in biodegradable organics which can lead to a rapid production of VFAs, reducing the pH of the media and inhibiting the activity of methanogens. The degradation of large quantities of proteins and lipids in food waste tends to cause reactor foaming, or produce high concentrations of inhibitory ammonia, hydrogen sulfide, and long chain fatty acids, all of which reduce system stability and methane yield [17,19].

Co-Digestion of Food Waste with Agricultural Residues On-Farm

Due to the various technical challenges of mono-digestion, co-digestion of food waste with other organic waste has been widely employed as one of the most technically ready options to supplement the required nutrients and increase system stability. It is also an economically viable option as food waste can be treated by existing on-farm digesters to avoid high capital investment. In addition, food waste can boost gas production from on-farm digesters, bring in tipping fee as an additional income to farms, and produce more energy for farms to use or sell. The most commonly used on-farm waste for co-digestion is animal manure, while crop residues, waste bedding materials, and fruit and vegetable wastes have also been intensively studied. Some examples are given in Table 4. Animal manures, such as dairy, swine, and poultry, can provide high buffering capacity, nitrogen, and a wide variety of macro- and micronutrients that are needed by the anaerobic microorganisms. Co-digestion of food waste with dairy manure was found to increase the maximum allowable organic loading rates of the digester, provide a more stable environment for anaerobic microbes, increase the degradation of lipids, and boost biogas production [25]. Co-digestion of swine manure with food waste increased biogas production by 80-400% [26], and the sensitivity of the AD process to environmental changes was also reduced [27].

Crop residues, such as corn stover and rice husks which have high C/N ratios and low degradability, have been widely studied as co-substrates for food waste. The purpose is to achieve a C/N ratio of 20-40 by balancing the high nitrogen content in food waste, and to reduce the overall VFA production rate. Co-digestion of food waste with crop residues was found to increase the AD organic loading rate [28]. In addition, crop residues have high production, wide availability, and relatively low utilization rate, thus are believed to be a promising substrate for AD. Currently, higher moisture crop biomass, such as silage and fresh energy crops, are more commonly used in AD, especially in European countries. For example, the annual biogas potential in Germany is calculated to be 24 billion m^3, mainly from energy crops [29]. While dry crop residues are still not commonly used, their high potential has been documented in numerous publications [30-32]. Another potential co-substrate for food waste in on-farm digesters is bedding materials derived from biomass, such as straw and sawdust. Other uses for these materials are limited, and the bedding process has been reported to partially degrade the fibrous materials and enhance their degradability in AD [33].

Co-Digestion of Food Waste with Sewage Sludge

Food waste produced in urban areas is commonly co-digested with sewage sludge, either in existing digesters in wastewater treatment plants or in other commercial digesters. The principle is similar to co-digestion of food waste with animal manure. Since sewage sludge, especially the secondary sludge from the activated sludge process (composed of large quantities of aerobic bacteria produced during wastewater treatment process), has low nutrient content and thus low methane yield, addition of food waste can boost biogas yield and improve sewage sludge degradation. Sewage sludge is also accepted in food waste digesters to bring in additional tipping fees, and compared to food waste mono-digestion, sewage sludge can provide alkalinity and micro-nutrients, thus reducing the cost of supplementing commercial buffers or trace elements [19]. Sewage sludge also contains large quantities of active microorganisms that can be beneficial for the AD process [34]. Examples of improved methane yield during sewage sludge and food waste co-digestion are shown in Table 4. The recommended mixing ratio of food waste and sewage sludge vary across the literature, but the most common range of added food waste was 33.3-50% (w/w total feed solids) [19]. However, the disadvantage of adding sewage sludge to food waste is that the residue digestate may be subject to more strict regulations during land application, due to the concerns of pathogens and heavy metals in the sewage sludge. The high concentration of salt in food waste is also a problem during the co-digestion and final land application [35].

Co-substrates	Temperature	The optimum co-digestion ratio	OLR (kgVS/ m^3/d)	Methane yield (m^3/kgVS_{added})		
				Co-digestion	100% food waste	0% food waste
Dairy manure	Mesophilic	Dairy manure (33%) + food waste (67%)	10	0.39	0.35	0.07
Dairy manure	Thermophilic	Dairy manure (27% w)+ food waste (73% w)	4.7	0.62	-	-
Piggery wastewater	Mesophilic	Dairy manure (17%COD) + food waste (83%COD)	6.4 (gCOD/ L/d)	0.39	-	-
Rice husks	Mesophilic	Food waste mixed with rice husks to a C/N ratio of 28	6	0.39	-	-
Maize husks	Mesophilic	Maize husks (25% w) + food waste (75% w)	4.5	0.72* (67% CH_4)	0.5*	0.24*
Maize husks	Mesophilic	Maize husks (25%) + food waste (75%)	-	0.71*	0.5*	0.24*
Livestock waste	Mesophilic	Livestock waste (40%) + food waste (60%)	-	0.26(g COD_{added})	-	-
Waste activated sludge	Mesophilic	Waste activated sludge (10%VS) + food waste (90%VS)	2.4	0.32	-	-
Dewatered sludge	Mesophilic	Dewatered sludge (47%VS) + food waste (53%VS)	5.1	0.35	-	-
Sewage sludge	Mesophilic	Sewage sludge (75%vol)+ food waste (25%vol)	-	0.44	-	-
* Volume presented as biogas						

Table 4: Co-digestion of food waste with agricultural residues and sewage sludge. Adapted from [19].

Conclusion and Remarks

Using food waste for AD is a promising direction for both waste management and energy production. However, this technology is still not mature and is facing many technical, economic, and social challenges. One important technical challenge is that when concise process control and optimization are lacking, harmful intermediate compounds, such as VFAs and hydrogen, can be easily produced, causing system instability and low methane yields. Also, the high protein and lipids contents in food waste easily generate inhibitory levels of ammonia, hydrogen sulfide, and long chain fatty acids, or cause digester foaming. As a result, AD of food waste often has to be performed at low OLRs to prevent process failure.

AD systems are capital intensive and their revenues are mainly from tipping fees of organic waste collection and biogas production. Increasing food waste loading and system stability are crucial for the economic viability of AD. Increasing the operating temperature or TS content are two ways to increase the loading of food waste, although both methods decrease digester stability and need careful control and optimization. Co-digestion with animal manure or sewage sludge are common practices to provide alkalinity and micronutrients for the AD process and to increase methane yield. However, contamination from these wastes, such as heavy metals, hormones, antibiotics, and pathogens, need to be controlled or eliminated, and clear standards should be established for the utilization of digestate to help establish a market for it.

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