What Role Can Anaerobic Digestion Play in Processing Compostable Packaging?

Insights from Europe and Key Learnings for the United States Market

CLOSED LOOP partners
CENTER FOR THE CIRCULAR ECONOMY

COMPOSTING CONSORTIUM

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SOURCE: ENVANTO

About Closed Loop Partners

Closed Loop Partners is at the forefront of building the circular economy. The company is comprised of three key business segments. Closed Loop Capital Management manages venture capital, buyout and catalytic private credit investment strategies on behalf of global corporations, financial institutions and family offices. The Center for the Circular Economy unites competitors and partners to tackle complex material challenges and implement systemic change to advance circularity. Circular Services employs innovative technology within reuse, recycling, remanufacturing and re-commerce solutions to improve regional economic and environmental outcomes, and build resilient systems that keep food & organics, textiles, electronics, packaging and more, in circulation and out of landfill or the natural environment. Closed Loop Partners is based in New York City and is a registered B Corp. For more information, please visit www.closedlooppartners.com.

About the Center for the Circular Economy

The Center for the Circular Economy ('the Center') is the innovation arm of Closed Loop Partners, a leading circular economy-focused investment firm in the U.S. The Center executes research and analytics, unites organizations to tackle complex material challenges and implement systemic change that advances the circular economy. The Center for the Circular Economy's expertise spans circularity across the full lifecycle of materials, connecting upstream innovation to downstream recovery infrastructure and end markets.

The Center's Circular Insights Lab conducts quantitative and qualitative research and data analytics through in-market pilots, focus groups, iterative testing and consumer interviews, identifying circular trends, challenges and opportunities across multiple sectors and themes, including reuse.

About the Composting Consortium

The Composting Consortium, managed by the Center for the Circular Economy at Closed Loop Partners, is a multi-year industry collaboration on a mission to build a world where organics are kept in circulation. The Consortium advances composting infrastructure and the recovery and processing of food-contact compostable packaging and food scraps in the U.S., to reduce food waste and mitigate climate impact.

The Consortium brings together leading voices across the composting and compostable packaging value chain—from the world's leading brands to best-in-class composters running the operations on the ground. Through in-market tests, deep research and industry-wide collaboration, the Consortium is laying the groundwork for a more robust, resilient composting system that can keep organics and compostable packaging in circulation.

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Executive Summary

SOURCE: ENVANTO

As the market for certified compostable packaging continues to grow, consumer product brands and manufacturers seek downstream solutions that can responsibly capture and process these materials. While food-contact, certified compostable packaging is designed to facilitate the diversion of food waste from landfill into an organics stream and then to composters, some municipalities divert post-consumer organic waste to anaerobic digestion infrastructure because of the existing presence of infrastructure or because of limited land availability to accommodate for composting. Since 2021, Closed Loop Partners and its Composting Consortium have extensively researched the requirements for successful large-scale processing of food-contact compostable packaging through full-scale commercial composting.

Compost manufacturers and anaerobic digestion facilities that accept food-contact compostable packaging and certified compostable bags view the packaging as a vehicle for increasing food waste flow to their operations. These operations are not designed to accept compostable products (e.g., compostable phone cases) that are not part of the organic waste stream. For this reason, this research focuses on anaerobic digestion infrastructure, specifically addressing the technical and operational feasibility of diverting food-contact compostable packaging through these systems.

Given the nascency of large-scale anaerobic digestion systems that process compostable packaging in the U.S., the Consortium connected industry learnings from the UK and European Union (EU) to the U.S. market. Large-scale anaerobic digestion refers to those facilities that process hundreds to thousands of tons of organic waste per day. Markets like the European Union (EU) are leading the way in processing compostable packaging, particularly liner bags used in source-separated food waste collection. This success is attributed to their well-developed infrastructure for integrating anaerobic digestion (AD) and composting, allowing them to effectively manage the compostable packaging stream on a large scale.

While large-scale anaerobic digestion holds promise for specific organic waste streams, research by the Composting Consortium suggests it may not be a viable solution for processing compostable packaging in the United States, at least not on its own. Several factors contribute to this limitation:

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System prevalence: The majority of industrial AD infrastructure in the U.S. are wet mesophilic systems, which operate at relatively low temperatures and may not be optimally designed to handle and adequately break down compostable packaging.

Pre-processing Limitations: Current mechanical depackaging technologies employed for AD lack the ability to differentiate between various packaging materials. This indiscriminate separation excludes all packaging from the AD process, hindering the potential for compostable packaging to enter the system and be effectively treated.

Limited Digestate Valorization: While the breakdown of compostable packaging is possible through subsequent composting of AD digestate, the widespread absence of established markets for this end product in the U.S. presents a substantial barrier to implementing this approach. If compostable packaging is to be value-additive to the anaerobic digestion value chain, we must ensure these materials are captured and processed as intended. Europe has several models that showcase the success of collaboration between AD operators and composters, driving innovation and best practices. The case studies in this paper highlight that this can be achieved through integrated business models that combine anaerobic digestion (generating renewable energy) and composting on a single site — creating capacity to process compostable packaging and make compost from the digestate. Strong partnerships among AD operators, composters and manufacturers are crucial in Europe. This collaboration fosters innovation in packaging design and pretreatment methods that align compostable packaging with AD recovery, ensuring smooth material flow and improving the entire organics management ecosystem. The symbiotic relationship between AD and composting industries are strenghtened by industry standards for digestate produced via anaerobic digestion of food waste and other feedstocks, which builds trust and incentive for composters. By addressing these challenges and learning from successful models in Europe, large-scale AD can potentially become viable in the U.S., alongside composting and other distributed organics recovery solutions. This would not only prevent contamination of recycling streams and diversion of compostable packaging to landfills but also potentially increase the amount of nutrient-rich food scraps available for AD and composting, maximizing resource recovery and contributing to a more flexible and sustainable future for organics management.

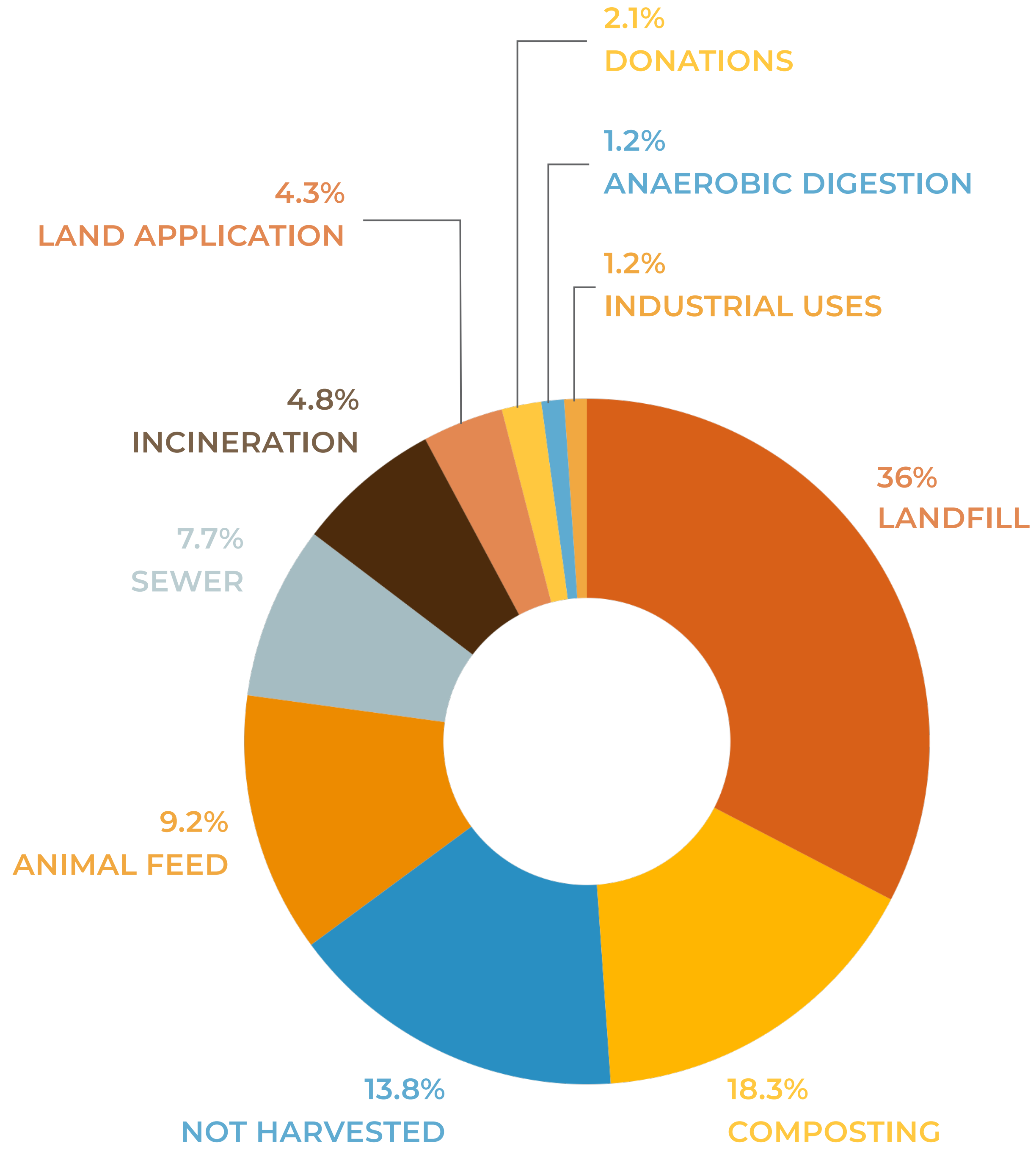
SOURCE: ENVANTO

Introduction

In the United States today, food waste that can no longer be consumed follows one of several pathways including landfill, composting, anaerobic digestion, or incineration. Food constitutes the predominant material in landfills, making up 24% of municipal solid waste[1]. Moreover, 61% of the methane produced by food waste in landfills is released into the atmosphere[2], contributing to greenhouse gas emissions and climate change. Composting and anaerobic digestion are pivotal systems to keep resources in use in a circular economy. AD employs microorganisms in an oxygen-deprived environment to convert organic waste, like food waste and biosolids, into energy and nutrient rich digestate. Conversely, composting, relying on oxygen, manages solid organic waste streams, producing compost as the end product. Identifying how best to deploy these systems is crucial for fostering sustainable practices aligned with a circular economy that mitigate environmental impact.

Closed Loop Partners (CLP) is at the forefront of building the circular economy and has invested in both AD and composting solutions closing the loop on food waste since 2013[3]. In 2021, CLP's innovation center, the Center for the Circular Economy, launched the Composting Consortium, a multi-year initiative that convenes the entire composting value chain to support the scale up of food-waste composting infrastructure that produces circular

FIGURE 1. END-OF-LIFE PATHWAYS FOR SCRAP FOOD IN THE UNITED STATES (2022)



SOURCE: REFED FOOD WASTE MONITOR, 2022 outcomes for compostable packaging and the food scraps it carries. While much of the Composting Consortium's focus is centered on composting infrastructure and food-contact compostable packaging, for this research, we sought to understand how AD might play a role in the recovery and processing of certified, food-contact compostable packaging since compostable packaging is expected to grow 16% each year until 2032 and since a growing amount of infrastructure for food waste AD is being constructed as municipalities seek to divert food waste from landfill. To do this work, Closed Loop Partners partnered with BioCycle Connect, LLC, and Target Renewables, Ltd., to identify the barriers and opportunities that exist for processing compostable packaging through AD. This study assesses the extent to which compostable packaging is currently processed within the existing AD landscape in the U.S. We also analyzed European and UK markets which have created viable pathways to utilize AD infrastructure as an end-of-life option for post-consumer food waste and certain certified compostable packaging. By examining and learning from these systems, we aim to identify insights applicable to the U.S. market.

Anaerobic digestion of food waste in the U.S. has been growing steadily over the past 10 to 15 years. As of 2019, a total of 275 AD facilities process food waste, including 68 stand-alone food-waste digesters, 79 on-farm digesters and 128 co-digestion systems at water resource recovery facilities[4]. Much of the food waste received by anaerobic digesters in the U.S. is pre-consumer food waste from food and beverage manufacturers, along with fats, oils and grease (FOG) and high-strength wastewater. However, more recently, states with food waste- to-landfill bans or mandates on food waste diversion have been increasing the flow of post-consumer food waste to anaerobic digesters. For example, the Commonwealth of Massachusetts requires that any commercial and institutional generator of 1,000 pounds per week or more of food waste divert it to organics recycling. Of the 357,844 tons of food waste diverted in 2022 in Massachusetts, 61% was processed by anaerobic digesters (primarily codigestion with manure or biosolids) and 9% was composted.

As an increasing amount of post-consumer food is directed to AD facilities, there is a higher probability of encountering various formats of compostable packaging in the stream. This includes items such as compostable caddy liners, cutlery, and other food serviceware packaging. This report specifically examines the viability of AD as a pathway to recover and process certified compostable food-contact packaging.

SOURCE: ENVANTO

What is Anaerobic Digestion?

Anaerobic digestion (AD) is a biological process that uses microorganisms – which can process wastewater sludge, food waste, livestock manures and fats, oils and grease – yields two outputs: energy-rich biogas and nutrient-rich digestate. The biogas can be utilized to generate electricity or upgraded in a further downstream process to biomethane, also known as renewable natural gas (RNG). Digestate consists of any remaining solids and liquids after digestion and can be used as a fertilizer or soil enhancement to promote plant growth and soil quality. The composition of digestate varies depending on the feedstock and the specific AD system used.

Technology Overview

In both the composting and AD processes, microorganisms like fungi and bacteria break down organic waste streams to produce different outputs with different end markets (i.e. biogas vs compost). Figure 2 illustrates both processes.

Large-scale AD systems fall broadly into three types (Table 1):

- Wet systems
- High-solids Anaerobic Digestion (HSAD)
- Dry batch systems

FIGURE 2. PROCESS FLOW OF AD AND COMPOSTING

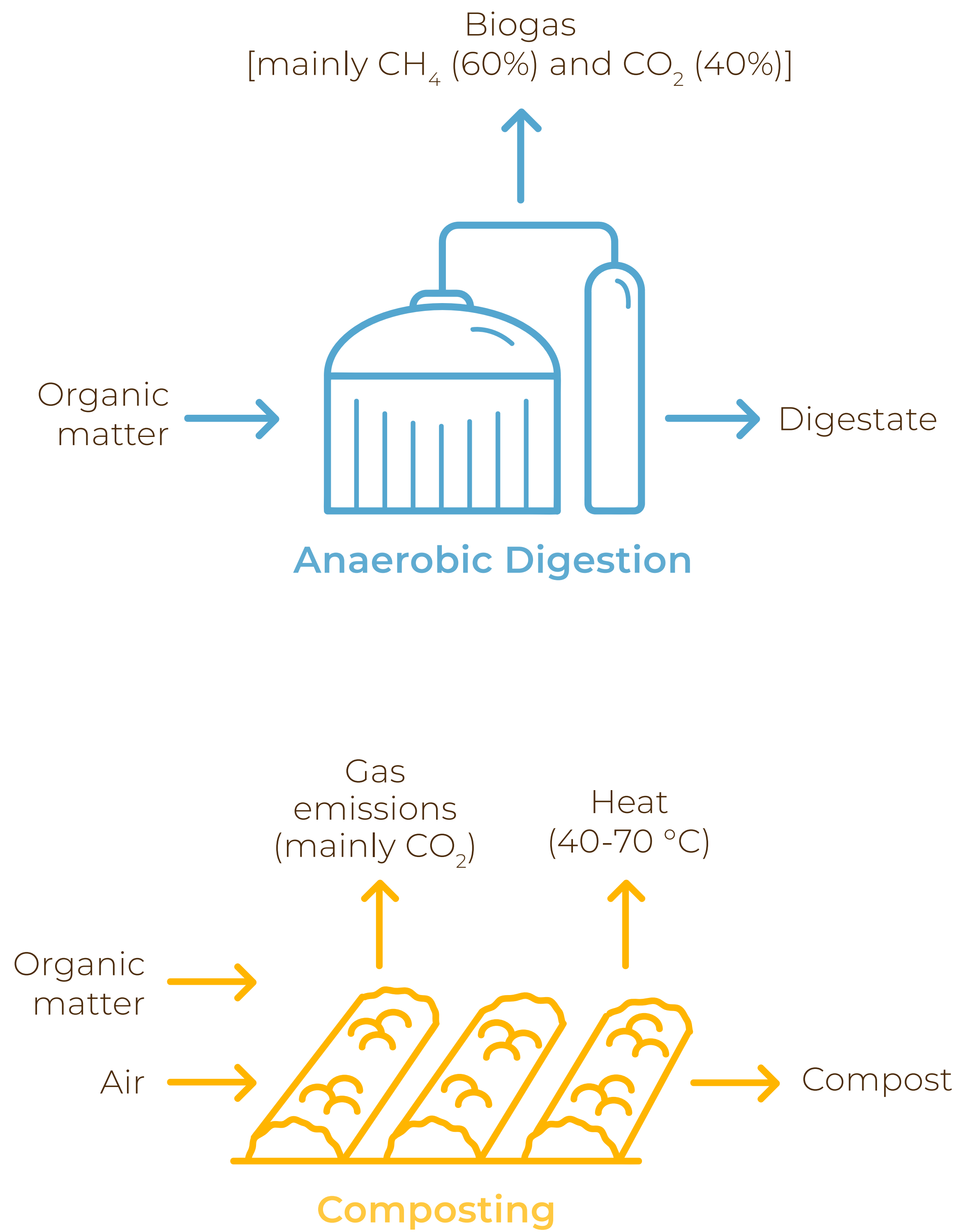


TABLE 1. PRINCIPAL CATEGORIES OF AD SYSTEMS AND THEIR KEY CHARACTERISTICS

AD SYSTEM	TYPICAL DRY SOLIDS CONTENT OF FEEDSTOCK*	SYSTEM STRENGTHS	SYSTEM WEAKNESSES
Wet-AD Systems (liquid)	<15%	· Continuous system · Widely available · Routine operation and use · Relatively low capital cost	· Unsuitable for contaminated and abrasive feedstock · Requires consistency of input material · Not able to handle seasonal variation in input quantity
High-solids Anaerobic Digetion (HSAD)	15-35%	· Continuous system with some seasonal flexibility · Able to handle contaminated feedstock · Typically, low operational costs and resource requirements · Integrates well with composting and technology 'hybrid' concepts	· Relatively high capital cost · Bespoke design and construction · Unreliable process flow-control at low Dry solids of the input material
Dry Batch Systems	>40%	· Integrates well with compost systems · On-off operation allows for seasonal variation in feedstock supply · Able to handle contaminated feedstock	· Unsuitable for liquid wastes or slurries · Relatively low gas yield

*REFERS TO APPROXIMATE COMBINED CHARACTERISTICS OF ALL MATERIALS IN THE FEEDSTOCK MIX

MESOPHILIC VS THERMOPHILIC AD

Mesophilic processes contain microorganisms that thrive and function in moderate temperatures around 99°F and can range between 68°-113°F. In contrast, thermophilic systems contain microorganisms that thrive and function in much hotter temperatures 130°F with ranges between 122°-147°F. It's common for thermophilic digestion to offer faster digestion but they also require more energy for heating.

These three AD categories fall into one of two temperature ranges: mesophilic or thermophilic. Both thermophilic and mesophilic digesters can be designed and operated as wet or dry systems. In wet systems, feedstocks are prepared into a slurry consistency and are loaded into the system using pumps. Higher solids feedstocks can be loaded via conveyors and/or loader buckets.

Different temperatures impact the microbial composition in anaerobic digesters, leading to distinct microbe communities in mesophilic and thermophilic systems. Microbes are crucial in breaking down compostable packaging in any AD system. How fast this breakdown happens depends, in part, on the temperature of the process, whether it's warm (mesophilic) or hot (thermophilic).

THREE TYPES OF AD SYSTEMS

FIGURE 3: A TYPICAL WET-AD FACILITY SHOWING ROUND TANK CONSTRUCTION OF THE DIGESTERS INTO WHICH LIQUID OR LIQUIDIZED FEEDSTOCK IS FED FOR DIGESTION WITHIN THE TANK, EQUIPPED WITH GENERAL MIXING OF THE SUBSTRATE

FIGURE 4: A TYPICAL PLUGFLOW HIGH SOLIDS AD (HSAD) FACILITY SHOWING THE BESPOKE NATURE OF CONSTRUCTION INTO WHICH FEEDSTOCK IS FED EITHER AS LIQUIDS OR SIZE-REDUCED SOLIDS TO TRANSIT THE DIGESTER FROM ONE END TO THE OTHER IN A CONTROLLED FLOW THROUGH THE SYSTEM

FIGURE 5: FILLING SOLID ORGANIC MATERIAL INTO A TYPICAL BATCH SYSTEM AD FACILITY USING A LOADER AT ONE UNIT IN THE ARRAY OF CHAMBERS

DISTRIBUTED ANAEROBIC DIGESTION SOLUTIONS

HomeBiogas, a Closed Loop portfolio company, designs and manufactures distributed AD solutions. Their user-friendly digester units empower individual households and communities to transform food scraps into clean biogas for energy and nutrient-rich fertilizer. They also partner with municipalities, commercial real estate developers, hospitality companies, restaurants, and waste management providers to implement large-scale, on-site solutions. Distributed AD solutions allow for greater control over contamination and prevent the need for trucks to haul the waste.

HomeBiogas

Feedstock Preprocessing

In the U.S. today, most AD facilities are wet mesophilic systems and have a low tolerance for non-liquid substrates, like compostable packaging. While many organic waste streams (e.g., wastewater, manure, high strength beverage waste) are already liquefied and can be pumped directly into tanks that feed anaerobic digesters, others need to be processed to have a slurry-like consistency. As a result, AD facilities are increasingly relying on mechanical depackaging equipment to process packaged foods, beverages and source-separated loads of commercial and residential food waste. Packaging and common contaminants, like conventional plastics, are removed and the food waste is slurried into a format the digester can accept. Food waste depackagers recover anywhere between 90 to 97% of food from its packaging, depending on how much food remains adhered to the packaging after separation.[5]

Unless it is manually sorted out ahead of mechanical depackaging (e.g., household food waste in compostable liner bags), all compostable packaging and liner bags will be removed during the separation process with recyclables typically being sent to material recovery facilities (MRFs) and the remaining residuals, including compostable packaging, disposed of.

In the case of high solids anaerobic digestion (HSAD) systems, feedstocks typically are mechanically shredded to increase their surface area prior to AD. For example, some HSADs digest food waste and shredded or ground yard trimmings together. If the food waste feedstocks are contaminant-free, those feedstocks can be shredded together, a practice used at food waste composting facilities. Some HSAD facilities utilize a mechanical depackager to separate out contamination, however the output is not slurried. Many HSAD systems also have a secondary composting step after AD (i.e. in-vessel composting system). The final compost is screened to remove contaminants that were not screened out before HSAD. It is common to see screens (e.g., trommels) equipped with an air classifier that facilitates separation of film plastic from the compost.

MECHANICAL DEPACKAGING

Mechanical depackagers are machines that shred and separate food-contact packaging from the food and liquid it protects. They are typically used for pre-consumer food waste (i.e., where the food or liquids are still in intact packaging). These machines are commonly used by anaerobic digesters and are increasingly utilized by the composting industry. Any packaging included in incoming food waste streams is removed by the depackaging process; depackaging technology today is unable to distinguish between different materials (i.e. conventional plastic or compostable plastic). In the context of AD, mechanical depackagers are equipped to yield a pumpable slurry with greater than 95% removal of contaminants. While depackaging is considered an effective pre-processing measure, recent research suggests the process can generate microplastics from conventional plastic packaging, contaminating the resulting slurry.[6]

FIGURE 6: DEPACKAGING EQUIPMENT REMOVES ALL PACKAGING FROM FEEDSTOCK

Anaerobic Digestion End Markets

Biogas Markets in the U.S.

The two outputs from an AD system are biogas and digestate. The biogas coming out of the digester is a mix of methane and carbon dioxide (CO_2), along with a smaller amount of contaminant gases such as hydrogen sulfide. The ratio of methane to CO_2 varies but ranges from 60% methane to 35% CO_2, with 5% other gases. The digestate from wet mesophilic digesters can be used directly on agricultural crops or separated into liquid and solid fractions. The liquids contain nutrients (e.g., nitrogen and phosphorus) that have value as a synthetic fertilizer substitute. The solids can be composted or used to produce a biochar. On-farm digesters often use the digestate solids in their operations. For example, dairy farms with digesters often use the separated solids as bedding for the cows.

BIOGAS INCENTIVES

Biogas has versatile applications: it can be directly used as a fuel in a boiler, or it can undergo cleaning to enhance methane content by removing CO2 and contaminants. Some digesters combust the purified gas in combined heat and power engines, while others go a step further by conditioning and compressing it into renewable natural gas (RNG). Digesters producing RNG often incorporate combined heat and power engines to offset the facility's power consumption. Heat recovered from these engines is then utilized to maintain the optimal operating temperatures, either mesophilic or thermophilic, in the digester.

"In recent years, anaerobic digestion has experienced significant growth, primarily due to financial incentives and policies emphasizing biogas as a low-carbon fuel."

One such policy is the U.S. Renewable Fuel Standard (RFS), overseen by the U.S. EPA, which mandates that all commercially sold transportation fuel in the U.S. must include minimum volumes of renewable fuels, reaching 20% by volume by 2022. The RFS, along with similar low-carbon fuel regulations in California and Oregon, encourages the production of Renewable Natural Gas (RNG) from biogas generated by landfills and anaerobic digesters. This RNG, equivalent to fossil natural gas, can be injected into natural gas pipelines or directly used in engines fueled by natural gas (such as Compressed Natural Gas or CNG).

Each gallon of renewable fuel under the Renewable Fuel Standard (RFS) has the potential to generate credits known as "Renewable Identification Numbers" (RINs). RINs serve as the currency within the RFS framework, utilized by obligated parties as a compliance mechanism to fulfill the annual renewable volume obligations (RVO) mandate. Obligated parties, including petroleum refiners and importers of refined fuel into the United States, can acquire RINs by producing qualifying renewable fuels, purchasing renewable fuels with attached RINs, or buying RINs separated from renewable fuels. These credits not only support compliance but also contribute additional revenue through the sale of Renewable Natural Gas (RNG) as a vehicle fuel. This enhances the economic viability of anaerobic digestion projects and attracts new capital to the industry.

The RIN credits market employs "D-Code" categories for pricing, with biogas from Anaerobic Digestion (AD) qualifying for D3 or D5 RINs. D3 RINs, as detailed in Table 2, favor cellulosic feedstocks like manure and biosolids, commonly managed by wet mesophilic systems. However, the EPA classifies food waste as a non-cellulosic feedstock, designating the produced biogas as a D5 RIN. Notably, D5 RINs have a significantly lower monetary value compared to D3 RINs generated from AD facilities digesting only manure or biosolids. Previously, digesters processing food waste were automatically assigned to the D5 RIN category, but a June 2023 final rule from the U.S. EPA introduced a formula to calculate the D3 RINs separately from the D5 RINs derived from food waste at co-digestion facilities. This means that a facility accepting food waste alongside manure or biosolids can now be eligible for D3 RINs and can potentially increase their revenue.
An emerging market for Renewable Natural Gas (RNG) generated by digesters accepting food waste includes institutions and companies with climate targets, seeking to "green" their natural gas supply to meet greenhouse gas (GHG) emissions reduction commitments. Additionally, some natural gas utilities are purchasing RNG through a green tariff, offering it as a premium to commercial and residential customers. In the voluntary purchase market, some anaerobic digestion facilities sell RNG at a lower price than the RIN credit, entering into long-term purchasing contracts in exchange.

The American Biogas Council notes that of the 105 stand-alone food waste digesters across the U.S., 21 are producing RNG. Of the RNG that is produced from these facilities, about 25% goes into the Renewable Fuel Standard (RFS) marketplace, earning D5 RINs; <1-5% is used in the voluntary market, like supplying corporate and institutional campuses. California's Low Carbon Fuel Standard, which rewards production of low-carbon fuels like RNG, has significantly boosted on-farm AD projects. Additionally, several food waste AD facilities have also qualified for these credits.. The majority of food waste digesters in the U.S.,70-75%, sell to natural gas utilities as a "green" gas option. These AD plants monetize the environmental attributes of the gas directly through a utility's Power Purchase Agreement, and not through RINs.

TABLE 2. AVERAGE RIN AND LOW CARBON FUEL CREDIT: PRICES PER RIN OR CREDIT BETWEEN 2022-2024

D-CODE	AVERAGE PRICE		
	2022	**2023**	**2024**
D3	$3.470	$3.487	$3.203
D4	$0.875	$0.851	$0.840
D5	$0.865	$0.830	$0.830
D6	$0.840	$0.843	$0.830
	AVERAGE PRICE		
CA LCFS Credit	$67.13		
OR CFP Credit	$105.00		

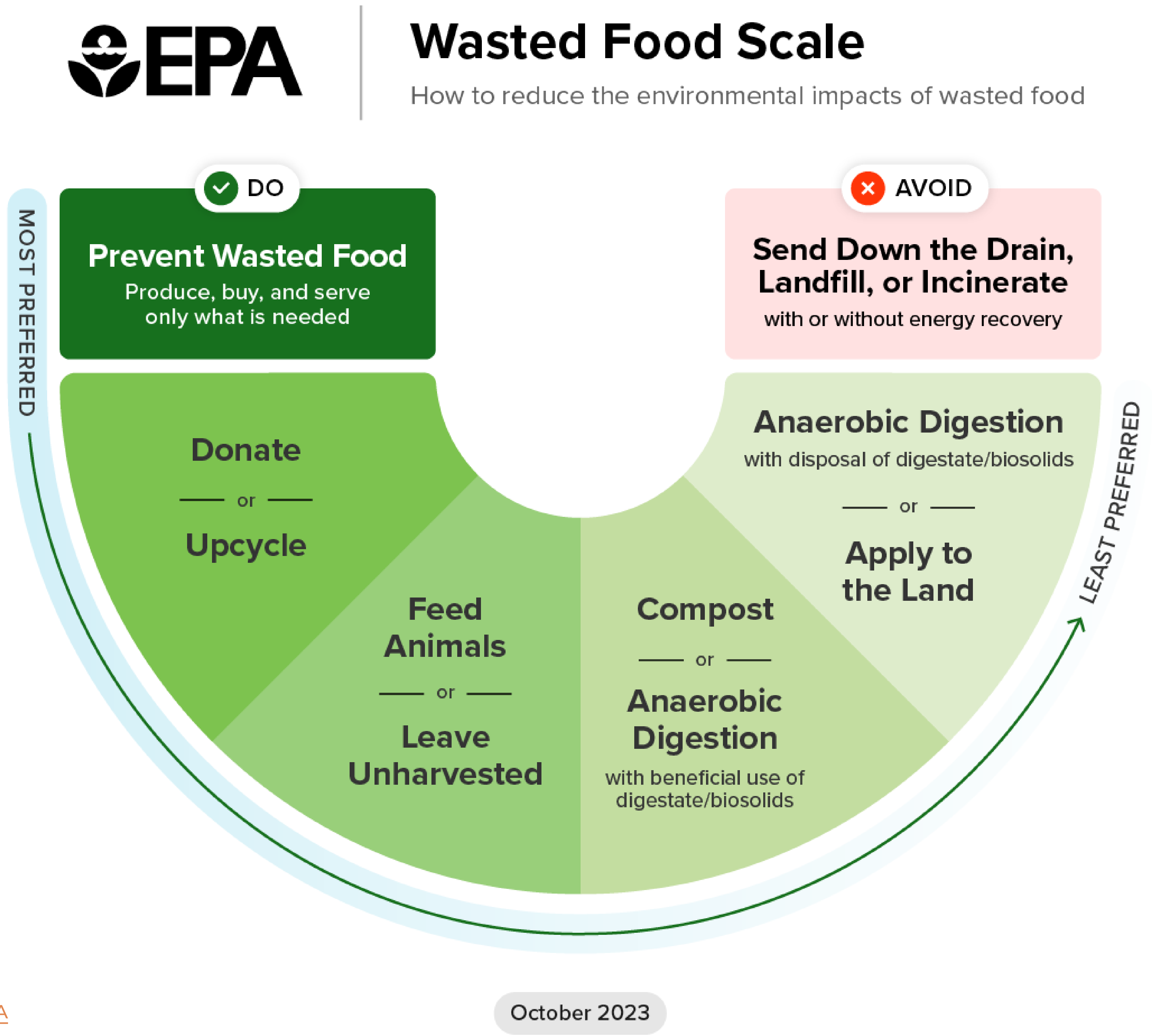
NOTE: CALIFORNIA AND OREGON ARE THE TWO STATES THAT CURRENTLY HAVE CLEAN FUEL STANDARDS THAT CREATE CREDIT MARKETS FOR RNG. WASHINGTON HAS ESTABLISHED A STANDARD, BUT THE MARKET STRICTURE IS NOT YET OPERATING.
SOURCE: ECOENGINEERS, NOV. 10, 2023.

Digestate Markets in the U.S.

In October 2023, the Environmental Protection Agency's (EPA) released its updated its Wasted Food Scale, ranking wasted food[7] pathways from most to least environmentally preferable, based on both a life cycle assessment (LCA) and a circularity assessment. After donation and upcycling of food waste, composting and anaerobic digestion with beneficial use of digestate or biosolids are ranked equally in the Wasted Food Scale in terms of the circularity and lifecycle (LCA) assessments (Figure 1). The vision for a sustainable organics system includes end markets for digestate. However, in the U.S., anaerobic digestion project developers and facility operators are not investing in digestate market development, and thus end markets for digestate have yet to develop.

Driven by current market incentives in the biogas sector, investors and facility operators prioritize anaerobic digestion of manure and biosolids to maximize RIN revenue over anaerobic digestion of food waste. With the focus on biogas and RIN credits, little attention has been paid to the value of digestate, and U.S. digestate markets remain underutilized. The liquid fraction of digestate contains high nutrient value as fertilizer for agriculture crops, but most anaerobic digestion facilities do not sell their digestate. Conversely,

FIGURE 7. MOST TO LEAST PREFERRED END OF LIFE SOLUTIONS FOR FOOD WASTE



SOURCE: EPA

the separated digested solids are not considered a finished product and require further maturation (e.g., via composting) to meet regulatory standards for use. As such, digestate currently has little monetary value in the U.S. and is only marginally composted.

In some instances, nutrient recovery technologies exist which are designed to recover nutrients like nitrogen and phosphorus from the digestate. These technologies are helpful when a facility must meet discharge standards on the effluent or must meet strict phosphorus limits if the digestate is being land applied. Wastewater treatment plants are often forced to install expensive nutrient recovery systems when facing strict federal clean water discharge standards, or try to decrease high nitrogen loads (such as food waste) into their operations. However, these technologies are expensive and still in the early phases of adoption.[8] In contrast, HSAD facilities typically compost the digestate, but six of these facilities exist across the U.S. today.

Is Anaerobic Digestion a Viable Pathway for Compostable Packaging?

U.S. Market Overview

This research aimed to identify regions across the United States where existing AD infrastructure can currently or could potentially process food-contact compostable packaging. Through comprehensive market analysis and stakeholder interviews, the following conclusions emerged regarding the current U.S. AD market:

1. **The U.S. biogas industry boomed in 2023 with record-breaking investments, but AD infrastructure continues to prioritize biosolids over stand-alone food digesters because of market incentives for renewable natural gas.** The U.S. biogas industry achieved its third consecutive year of record growth in 2023, with 96 new projects adding $1.8 billion in investments. The majority of investment capital has been directed primarily at the agricultural sector, attributed primarily to market incentives for renewable natural gas (RNG) made from livestock manure. According to the American Biogas Council, landfill gas accounts for 57% of 2023 capital investments and a corresponding 67% of new U.S. biogas production capacity. In 2023, the biogas industry saw significant growth with 70 farm-based projects totaling over $700 million in investments. However, stand-alone food waste digesters received a smaller share, with only 3 new projects starting in 2023, representing $78.7 million, or 6% of the industry's total investment.[9]

2. **Wet mesophilic anaerobic digestion facilities in the U.S. today do not process compostable packaging.** Our research did not identify any industrial wet anaerobic digestion facilities in the U.S. without mechanical depackaging for food waste streams (i.e. compostable packaging ends up in landfill), nor any wet mesophilic facilities that include compostable packaging as an accepted feedstock. While mesophilic digesters are proficient at handling nitrogen-rich waste like food waste, they are not suited as an end-of-life solution for compostable packaging since these materials exhibit slower rates of degradation in the lower-temperature systems and are therefore removed prior to anaerobic digestion.

3. **Thermophilic anaerobic digestion might be more suitable to process compostable packaging due to its higher temperatures, but it's not an ideal solution for processing food waste.** Biogas yields from food waste feedstocks are optimized at mesophilic temperatures. As such, thermophilic systems are less efficient at handling high-nitrogen feedstocks like food waste, but they would excel in processing compostable packaging. This efficiency

is attributed to conditions favoring microbial communities adept at rapidly breaking down compostable products and packaging, particularly compostable bioplastics which break down quickly under hot temperatures. A wet mesophilic AD facility could process compostable packaging if it has a back-end composting operation and the digestate is composted (i.e. compostable packaging goes through thermophilic temperatures while being composted). This would optimize biogas generation from food waste through the mesophilic process and enable disintegration of the compostable packaging through the thermophilic processes.

4. **In the U.S., a handful of High Solids Anaerobic Digestion (HSAD) and dry batch systems could technically process both packaging and organics like yard trimmings, but concerns about contamination are a barrier for compostable packaging to be processed.** These systems, accommodating larger feedstocks, are well-suited for handling compostable packaging. However, our research and interviews indicate that none of these six facilities in the U.S. intentionally accept compostable packaging—largely due to concerns about contamination from 'look-alike' conventional plastic packaging.

This concern for a potential increase in contamination mirrors the sentiments that many composters have about diverisfying the feedstocks they accept to include post-consumer food waste and compostable packaging.

The underexplored landscape of AD for compostable packaging in the U.S. led us to delve into this area. Recognizing the limited research on the efficacy of AD for processing such packaging domestically, we conducted a comparative analysis with systems in the European Union and the United Kingdom. This approach is particularly valuable because these regions boast a more robust AD infrastructure and extensive experience in handling compostable materials. By drawing upon their expertise, we aim to enhance our understanding and provide valuable insights in the context of the U.S. landscape.

What Can We Learn from European Markets?[10]

In this section, we delve into the European and UK markets to explore how AD and composting have been integrated, fostering a symbiotic relationship between the two industries. Unlike in the U.S., where AD and composting often operate independently, these regions showcase a cohesive approach. In Europe, curbside-collected household food waste from a local waste authority is directed to an AD facility and can include certified, food-contact compostable packaging. Compostable liner bags are the most common compostable packaging in the stream, each containing one household's food waste. Compared to commercial and industrial food waste streams, household organic streams tend to be relatively consistent (i.e. changes in composition tend to be seasonal rather than daily or weekly). In contrast, commercial and industrial organic waste in the EU and UK – from supermarkets for example – is likely to be much more variable and a mix of conventional plastic film, conventional rigid plastic, various formats of compostable packaging, paper and cardboard, etc. In the case of commercial and industrial waste the most common strategy is to treat the entire waste stream as contaminated and to install pre-treatment equipment to remove packaging whether it is suitable for the AD process. In the UK, the AD infrastructure is not designed to accept compostable packaging, according to a guidance[11] from WRAP, the UK's waste reduction program. The primary pathway for compostable packaging in the UK is through in-vessel composting facilities.

COMPOSTABLE PACKAGING IN WET MESOPHILIC AD SYSTEMS

Wet mesophilic AD facilities in the UK have encountered operational challenges when processing compostable packaging. These challenges primarily stem from the physical properties of the partially degraded bags after entering the digester. The bags tend to form a floating layer that hinders biogas release from the top of the digester and can also tangle in the mixing equipment, inhibiting efficient mixing and microbial decomposition. Additionally, the degradation process can lead to long, rope-like strands of material that require removal and disposal as contaminants.

Furthermore, large quantities of compostable packaging in the digester can negatively impact process stability. The floating layer reduces the effectiveness of the mixers and the usable volume of the digester, leading to decreased biogas yield. As the bags degrade, they absorb moisture, impacting the dry solids content of individual particles and the overall mix. This, in turn, affects the flowability and pumpability of the digestate.

If the digestion mass contains a significant amount of partially degraded compostable packaging, it may exhibit a "sticky" appearance or feel. Achieving the necessary agitation within the digester tank under these conditions requires more energy compared to dealing with dry solids alone. These circumstances are particularly relevant to wet AD, where the operational efficiency can be adversely affected. These findings highlight the importance of careful management of compostable packaging within wet AD systems to ensure optimal process performance and prevent operational issues.

COMPOSTABLE PACKAGING IN HIGH SOLID AD SYSTEMS

On the other hand, high solid anaerobic digestion (HSAD) is typically designed to deal with difficult-to-mix blends of material and typically has a much higher inertia so can handle these sorts of loadings. HSAD systems simply tend to keep turning material at the same speed almost irrespective of whatever is thrown at them.

In thermophilic AD with post-anaerobic digestion composting, compostable packaging can be processed via the AD process or handled as a split-stream combined AD and composting process. This scenario is most commonly in place for HSAD systems in Europe capable of handling commingled streams, e.g., of yard trimmings and food waste with compostable packaging. The solid digestate fraction from HSAD, which

FIGURE 8: 'ROPES' OF UNDEFINED COMPOSTABLE PLASTIC MERGING IN A MESOPHILIC WET DIGESTER TO FORM A FLOATING LAYER

FIGURE 9: CLOSE UP OF COALESCED COMPOSTABLE PLASTIC FORMING A FLOATING LAYER IN A MESOPHILIC WET DIGESTER

usually contains harder, larger particles such as yard trimmings and wood chips, tends to look and behave more like a three-month old windrow composted material, perhaps with just a little visible moisture. This type of solid fraction from HSAD is generally highly compostable.

In general, fresh HSAD digestate undergoes the stability and maturation process in weeks, a significantly shorter timeframe compared to composting the fresh feedstock without AD, which would take months. By the time the organic material reaches the composting stage in a hybrid system, roughly 70% or less of the original feedstock would be diverted to composting. Consequently, in-vessel composting (IVC) that follows an AD step, would be smaller than a standalone IVC facility without an AD step. However, this variation depends greatly on the physical characteristics of the feedstock.

WHERE HAVE HYBRID SYSTEMS BEEN SUCCESSFUL?

This idea of integration – also known as co-location or hybrid models – is one that is evolving and growing in the AD industry. In the European Union, these hybrid models appear to be the most favorable solution for processing compostable packaging. Here, we explore two case studies in greater detail.

SOURCE: ENVANTO

Case Study 1: Forsbacka near Gävle, Sweden

TECHNOLOGY: Hybrid HSAD system and in-vessel compost facility. HSAD system is thermophilic.

FEEDSTOCK: Range of organic waste, including curbside organics that contain compostable kitchen caddy liners, paper bags and compostable bags.

PRE-PROCESSING: Solid input material including packaged food waste is subject to minimal pre-treatment using a bag opener/pre-screen to size reduce to approximately 2.5 inches. Yard waste is separately received and shredded using a high-speed mobile shredder. Solids are placed in a buffer storage bunker which then feeds to the digester while liquids are direct-fed from reception tanks.

DIGESTATE PLAN: After AD, the digestate is separated into solid and liquid fractions using a screw press and vibrating screen. This dewaters the material, reducing the moisture content of the solids. The liquid fraction, which contains soluble nutrients like ammonium, is stored in tanks to be used as agricultural fertilizer. The dewatered solid fraction requires further processing through aerobic composting to stabilize and mature it into a finished product, which is screened after seven to 10 days (Figure 11).

THE RESULT: Higher specification compost for use in horticulture or as agricultural fertilizer and biogas is used for waste fleet vehicles and city buses.

FIGURE 10: INTEGRATED HIGH-SOLIDS AD WITH IN-VESSEL COMPOSTING FACILITY IN FORSBACKA, SWEDEN

FIGURE 11: AFTER A RETENTION TIME OF 30-35 DAYS, DIGESTATE IS DEWATERED, COMPOSTED, THEN SCREENED.

Case Study 2: Nokia's Facility near Tampere, Finland

TECHNOLOGY: A twin-track hybrid facility with both a continuous plugflow Dry-AD (HSAD) and a wet-AD line with centralized control and coordination. Both AD lines are thermophilic. All post-AD digestate is dewatered and the solids finished in a comprehensive in-vessel composting (IVC) facility to achieve the required national and European Union (EU) standards for product quality and biosecurity.

FEEDSTOCK: Range of organic waste including residential food waste, compostable kitchen caddy liners, commercial packaged food waste, commingled yard waste, various sludges and dewatered biosolids.

PRE-PROCESSING: Prior to AD, the residential stream (yard waste and food waste) is processed in a slow speed shredder with a metal separator and screened to remove contaminants including most conventional film plastic. Commercial food waste is depackaged using a hydraulic press. The relatively vigorous pre-treatment tends to tear rather than remove relatively soft compostable packaging. Separated organic material is conveyed via belt conveyors to a storage bunker.

DIGESTATE PLAN: All post-anaerobic digestion digestate is dewatered and the solids finished in in-vessel composting facility to meet the required national and EU standards for product quality and biosecurity.

THE RESULT: High quality horticultural grade compost and liquid fertilizer for application to agricultural land and biogas used to fuel local waste collection vehicles and can be exported to grid.

FIGURE 12: MUNICIPAL ORGANIC WASTE PRE-TREATED AND PROCESSED AT A HYBRID WET + DRY + IN-VESSEL COMPOSTING FACILITY IN NOKIA, FINLAND

FIGURE 13: SOLID DIGESTATE IS MOVED TO NEXT PROCESSING STEP AT THE INTEGRATED IN-VESSEL COMPOSTING PLANT

Key Insights from European AD Markets

1. **AD and Composting can work symbiotically:** AD and Composting can work symbiotically: Viewing AD holistically as a process that produces renewable energy and a high-value soil amendment — versus solely valued for its energy — creates symbiosis with composting infrastructure. Time required to produce finished compost is shorter, reducing the footprint of the composting area at the facility. In some cases, the digestate is composted at a separate location, e.g., a commercial composting facility or a farm.

   Developing and scaling viable end markets and products for digestate could enable AD facilities to become collection points for compostable packaging and other organics. Some facilities are exploring processes like drying, pelletizing, and nutrient extraction to create higher-value soil amendment products from digestate. Stronger markets and financial incentives for digestate utilization will be key for facilities to maximize its value, including potential recovery of compostable packaging. Partnerships between anaerobic digesters and composters could also help grow infrastructure for diverting and processing compostable materials.

2. **Build organic processing infrastructure to be adaptable and flexible:** European markets bypass limitations of single-stream AD by pioneering hybrid models. Food waste and compostable packaging undergo co-digestion, maximizing biogas and breakdown. The remaining digestate then funnels to composting. While hybrid AD and composting systems can have higher capital and operating costs (i.e., CAPEX and OPEX), the examples highlighted in this report illustrate how operators are maximizing the economic and environmental benefits of organics recycling by producing energy and valuable compost. This win-win approach overcomes inherent challenges of both pure AD and composting.

   The European market has scaled AD infrastructure based on the premise that mesophilic AD was an ideal solution. However, this market has scaled a relatively narrow approach focused predominantly on energy production from organic waste. The call for flexible solutions to organic waste is arising, emphasizing the importance of implementing systems that align with specific needs rather than a one-size-fits-all mentality.

3. **Collaboration Catalyzes Success:** Integrating compostable packaging with AD thrives on extensive collaboration and knowledge exchange. Europe showcases close partnerships between AD operators, composters, and manufacturers, fostering innovation and best practices. These collaborations not only ensure smooth material flow but also drive improvements in packaging design and pretreatment methods for optimal AD compatibility. Supportive policies, including feedstock quality regulations and financial incentives for hybrid facilities, further incentivize adoption and build a robust ecosystem for managing compostable packaging waste effectively.

Conclusion

This report aims to provide an initial assessment of the feasibility of integrating compostable packaging into existing AD systems, paving the way for informed decision-making and ultimately enabling a more sustainable future for our waste streams. In the United States, the dominant AD systems in place are wet mesophilic systems, which require liquefied feedstock made of organic matter (i.e. slurry) that is packaging-free. Introducing packaging materials into the feedstock can disrupt the AD process, necessitating careful consideration of potential operational challenges and reduced biogas production. While wet mesophilic AD systems efficiency produce biogas, the technology is less flexible to accepting diversified feedstocks, for example food waste containing compostable packaging. Other AD systems, like high-solids and dry batch AD systems, are technically capable of processing such compostable packaging, but U.S. operators avoid it altogether in the U.S. due to concerns about contamination.

Based on current market drivers, pre-processing methods, and prevalent technologies, current large-scale U.S. AD infrastructure is ill-equipped to handle compostable packaging at scale. As we think about the systems change needed to reach zero-waste, it will be critical to scale solutions that effectively address the complexities of post-consumer food waste management.

While utilizing existing Anaerobic Digestion (AD) infrastructure to process post-consumer food waste and certified compostable packaging presents promising possibilities, valuable lessons can be learned from European and UK experiences to optimize this approach in the U.S. market. Here are some key steps:

- **MINIMIZE DEPACKAGING:** For source-separated food waste streams containing food-contact packaging, minimize the use of depackaging equipment. This ensures the packaging remains in the AD feedstock, maximizing its resource recovery potential.
- **HYBRID MODELS:** Explore the potential of co-located high-solids AD and composting facilities. These hybrid models can efficiently process both food waste and food-contact compostable packaging. Conversely, wet mesophillic AD systems can be paired with a composting facility, but the compostable packaging has to be managed outside of the AD process.
- **HIGH-VALUE DIGESTATE MARKETS:** Develop profitable end markets for the composted digestate produced by these facilities. This creates additional revenue streams and incentivizes investment in such hybrid models.
- **BIOGAS INCENTIVES:** Encourage the use of biogas generated from food waste by activating existing pathways within the federal Renewable Fuel Standard, such as the e-RIN pathway for electric vehicle charging. Additionally, invest in infrastructure to enable the use of food waste-derived renewable natural gas (RNG) to decarbonize the fossil gas supply.

To fully realize this vision, further research is needed on the efficacy of AD with various compostable materials. Additionally, enhanced collaboration between AD operators, composters, and packaging manufacturers, along with supportive policy changes favoring hybrid models and promoting source separation, are crucial for successful implementation.

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LEARN MORE ABOUT THE CENTER FOR THE CIRCULAR ECONOMY'S WORK TO SCALE THE RECOVERY OF FOOD WASTE AND FOOD-CONTACT COMPOSTABLE PACKAGING

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