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Commercial Pre-Processing Technologies

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Executive Summary

Food waste—defined as food that is produced for human consumption but not ultimately consumed by humans—is a major global environmental, social, and economic challenge. Recognizing the critical importance of reducing food loss and waste, in 2015 the U.S. Environmental Protection Agency (EPA) and U.S. Department of Agriculture announced the *U.S. Food Loss and Waste Reduction Goal* to halve food loss and waste by 2030. One of EPA's strategies to help meet this goal is to encourage diversion of food waste from landfills to reduce methane emissions and recover value (i.e., nutrients or energy) from food waste. In addition, some states, like California, Massachusetts, and Vermont, and municipalities, like Austin, Boulder, and New York City, are instituting bans on landfilling food waste or implementing new recycling programs to reduce the amount of food waste sent to landfills and incinerators. To meet these new regulations and/or to meet their own economic and environmental goals, some commercial and institutional generators of food waste—including grocery stores, restaurants, hotels, universities, and correctional facilities— are installing on-site food waste pre-processing technologies.

In this issue paper, EPA seeks to assess the environmental value of commercial food waste pre-processing technologies to understand whether (and, if so, under what conditions) each class of these technologies can (a) enable or increase the recycling of food waste; and/or (b) reduce the overall environmental impact of food waste, and thus inform whether policymakers should encourage the use of each class of pre-processing technology. The paper discusses each of following five general categories of these technologies:

- Grinders, which mechanically reduce the volume of food waste by macerating it into a slurry;
- Biodigesters, which biologically treat food waste under aerobic conditions with additives like microbes, enzymes, and fresh water to digest the waste into a slurry;
- Pulpers, which mechanically reduce the volume of food waste by compressing it into a semi-dry pulp;
- Dehydrators, which thermally treat food waste to evaporate the liquid and create a dry pulp; and
- Aerobic in-vessel units, which use the natural aerobic decomposition process and bulking additives like sawdust to create a semi-dry product that requires further curing.

Each pre-processing technology requires different inputs and creates different outputs, and technologies may be used in combination with one another at a single facility. While almost no independent, peer-reviewed life cycle assessments have been performed on these technologies, many helpful insights exist in the literature.

Food waste can be recycled to produce biogas and/or soil amendments with or without pre-processing at the waste generation site, and the use of on-site pre-processing technologies does not guarantee recycling. However, all these technologies require source separation of food waste from inorganic waste, which is an important first step toward recycling. Once food waste is separated, food waste can be recycled on-site or hauled off-site to a composting, anaerobic digestion (AD), or other recycling facility.

Pre-processing technologies that produce liquid outputs (grinders and biodigesters) typically send the output down the drain. Whether biogas is recovered from the food waste is dependent upon whether the receiving wastewater resource recovery facility (WRRF) has AD capabilities. After treatment (with or without AD) at a WRRF, biosolids remain. These biosolids may be recycled (with or without further processing) and land applied as a soil amendment – or they may be landfilled.

In general, pre-processing technologies that send liquefied food waste down the drain shift the burden of food waste management from landfills to municipal sewage systems and WRRFs. The net environmental burden of this shift has not been thoroughly explored in the literature. Sending additional organic waste, high in biological oxygen demand (BOD), total suspended solids (TSS), and fats, oils, and grease (FOG), through the sewer can result in fugitive methane emissions and may require additional energy for pumping systems and water treatment processes. This waste can also cause operational problems for the water treatment systems, especially in low flow, combined, or aging systems. The shift could also be financial: commercial food waste generators that send liquefied food waste down the drain avoid paying tipping fees to landfills, but unless fees are imposed on the generators by the WRRF, municipal ratepayers may bear the added costs of sewer maintenance and additional treatment. In addition, many of the concerns with these technologies could multiply in scale if grinders and/or biodigesters become more broadly adopted among commercial food waste generators.

However, generators may also choose to collect liquid outputs from grinders or biodigesters and haul them off-site for biogas recovery via AD at a stand-alone AD or an AD at a WRRF. Food waste may lose energy potential as it travels through the sewer system and earlier parts of the WRRF. Available data indicates greater greenhouse gas (GHG) emissions benefit for trucking effluent from the generator to an AD unit versus sending the same effluent via sewer conveyance to a WRRF with AD. Biosolids will remain and, as above, may be recycled and land applied, or landfilled.

For technologies that produce semi-dry or dry outputs (pulpers, dehydrators, aerobic in-vessel units), generators must decide where to send the output. Generators may recycle the pre-processed food waste into a stable soil amendment by hauling it off-site for centralized composting or, in the case of dehydrators and aerobic in-vessel units, by further curing it on-site or off-site. The soil amendments created by dehydrators and aerobic in-vessel units are not compost in the traditional sense, and much remains to be learned about their stability and suitability for different uses. Facilities may also send the semi-dry or dry pre-processed food waste to a landfill or incinerator. The dry outputs are lower in weight and volume than unprocessed food waste, so if it is sent off-site, hauling-related fuel use and GHG emissions are reduced. Pulper and dehydrators remove water from the food waste and typically send this water down the drain, which may raise similar concerns to those noted above for grinders and biodigesters.

Based the current state of available research, EPA cannot conclude whether the environmental benefits of pre-processing commercial food waste (and sending the pre-processed waste to a composting or AD facility, WRRF, landfill, or incinerator) are greater than simply hauling unprocessed waste directly to the intended destination. EPA encourages the diversion of food waste streams to composting or AD operations, rather than landfills and incinerators, but cannot yet conclude whether or how the use of pre-processing technologies changes the environmental benefits or impacts of these choices. Scientifically rigorous data are needed to complete a life cycle assessment of the use of on-site pre-processing technologies in addition to, or in lieu of, traditional food waste pathways. Priority research gaps include:

- Independently verified operating and performance data for pre-processing technologies.
- Measurement of fugitive methane emissions from sewer conveyance of food waste.
- Comparative analysis of biogas potential of food waste that has been unprocessed, pre-processed by grinder, or pre-processed by aerobic digester, and then sent down the drain to a WRRF with AD or hauled directly to the AD unit.
- Environmental and economic impacts on municipal sewer systems and WRRFs of additional liquefied food waste (from grinders and biodigesters) and wastewater extracted from food waste (from pulpers and dehydrators) being sent down the drain.
- Effect of pre-processing technology use on food waste generators’ decision whether or not to recycle (i.e., does pre-processing technology use encourage or discourage recycling).

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Acronyms

AD	anaerobic digestion
BOD	biological oxygen demand
EPA	U.S. Environmental Protection Agency
FOG	fats, oils, and grease
GHG	greenhouse gas
LCA	life cycle analysis
MRF	mixed materials recovery facility
MSW	municipal solid waste
TSS	total suspended solids
USDA	U.S. Department of Agriculture
WERF	Water Environment Research Foundation
WRRF	wastewater resource recovery facility

1. INTRODUCTION

The purpose of this issue paper is to assess the environmental value of food waste[1] pre-processing technologies (e.g., biodigesters, grinders, and pulpers) used on-site by businesses and institutions that generate food waste. EPA seeks to understand whether (and, if so, under what conditions) pre-processing technologies can (a) enable or increase the recycling of food waste; and/or (b) reduce the overall environmental impact of food waste. The issue paper also identifies research gaps, where new research may help to inform whether U.S. federal, state, and local policymakers should encourage the use of each class of pre-processing technology to meet environmental objectives.

1.1. Background

Wasted food is a major global environmental, social, and economic challenge. Preventing food waste can save natural resources and avoid a myriad of environmental impacts, and recycling unavoidable food waste, such as inedible peels and bones, can reduce greenhouse gas (GHG) emissions and improve soil quality. In the United States today, food waste is typically landfilled or incinerated. The U.S. Environmental Protection Agency (EPA) estimates that more food reaches landfills and incinerators than any other single material in our everyday trash, constituting 24 percent of landfilled municipal solid waste (MSW) and 22 percent of combusted MSW (U.S. EPA, 2020).

In 2015, the EPA and U.S. Department of Agriculture (USDA) announced the *U.S. Food Loss and Waste Reduction Goal* to halve per capita food waste at the retail and consumer level (including consumer-facing businesses and institutions) by the year 2030. To date, thirty three businesses and organizations have publicly committed to halve FLW in their U.S. operations by 2030 as part of EPA's Food Loss and Waste 2030 Champions group, and two-thirds of the world's 50 largest food companies have set a similar FLW reduction target (U.S. EPA, 2020; Flanagan et al., 2019). In addition, some states, like California, Massachusetts, and Vermont, and municipalities, like Austin, Boulder, and New York City, are instituting bans on landfilling food waste or implementing new recycling programs to reduce the amount of food waste sent to landfills and incinerators. For example, Massachusetts banned the landfilling of commercial organic waste by businesses and institutions that dispose of 1 ton or more of organics per week (MassDEP, 2020). California requires commercial and public entities that generate over 4 cubic yards of organic waste per week to arrange for food waste recycling services to pick up their waste (CalRecycle, 2020b).

Many commercial generators of food waste are seeking methods to reduce the amount of food waste they send to landfills and incinerators. Large-volume generators of food waste—including grocery stores, restaurants, hotels, universities, and correctional facilities—have several choices once they have separated food waste from inorganic waste. A common strategy is to have a third-party hauler pick up and deliver the waste to a centralized composting or anaerobic digestion (AD) facility or to a farm for use as animal feed (RecyclingWorksMA, 2018; Goldstein and Dreizen, 2017; Gorrie, 2015).

Commercial food waste generators can also utilize on-site pre-processing technologies that either reduce the weight and volume of food waste (thus reducing the cost, difficulty, and GHG emissions associated with hauling food waste) or break down and liquify the food waste to the point that it can sent directly down the drain into the existing municipal sewage system or captured in a vessel that can be transported to an AD facility. Some pre-processing technologies provide additional advantages for commercial food waste generators, including minimizing odors and storage space needed for food waste.

The U.S. market for on-site commercial food waste pre-processing technologies is small, but has grown during the past decade (Goldstein and Dreizen, 2017). A diverse range of mechanical, thermal, or biological options are

[1] In this paper food waste is defined as food that is produced for human consumption but not ultimately consumed by humans.

available. The following five general categories of these technologies are each discussed in detail in this issue paper:

- Grinders, which mechanically reduce the volume of food waste by macerating it into a slurry;
- Biodigesters, which biologically treat food waste under aerobic conditions with additives like microbes, enzymes, and fresh water to digest the waste into a slurry;
- Pulpers, which mechanically reduce the volume of food waste by compressing it into a semi-dry pulp;
- Dehydrators, which thermally treat food waste to evaporate the liquid and create a dry pulp; and
- Aerobic in-vessel units, which use the natural aerobic decomposition process and bulking additives like sawdust to create a semi-dry product that requires further curing.

Each pre-processing technology requires different inputs and creates different outputs, and technologies may be used in combination with one another at a single facility. This issue paper describes each of the five pre-processing technologies listed above, including the types and capacities of food waste that may be processed, the resources (such as water and energy) required to operate the technologies, and the availability and use of the technology in the United States. A discussion of environmental considerations related to each technology follows.

After using one or more pre-processing technologies, commercial food waste generators must also manage the products or effluents. For example, a liquid product may be disposed of down the drain (if allowed), a dry pulp can be processed into compost, or a reduced weight and volume of food waste may simply be hauled to a centralized composting facility, AD facility, landfill or incinerator. The issue paper concludes with a summary of the environmental considerations associated with food waste pre-processing technologies, information gaps, and research needs.

Figure 1 provides an overall summary of the available information on pre-processing technologies.

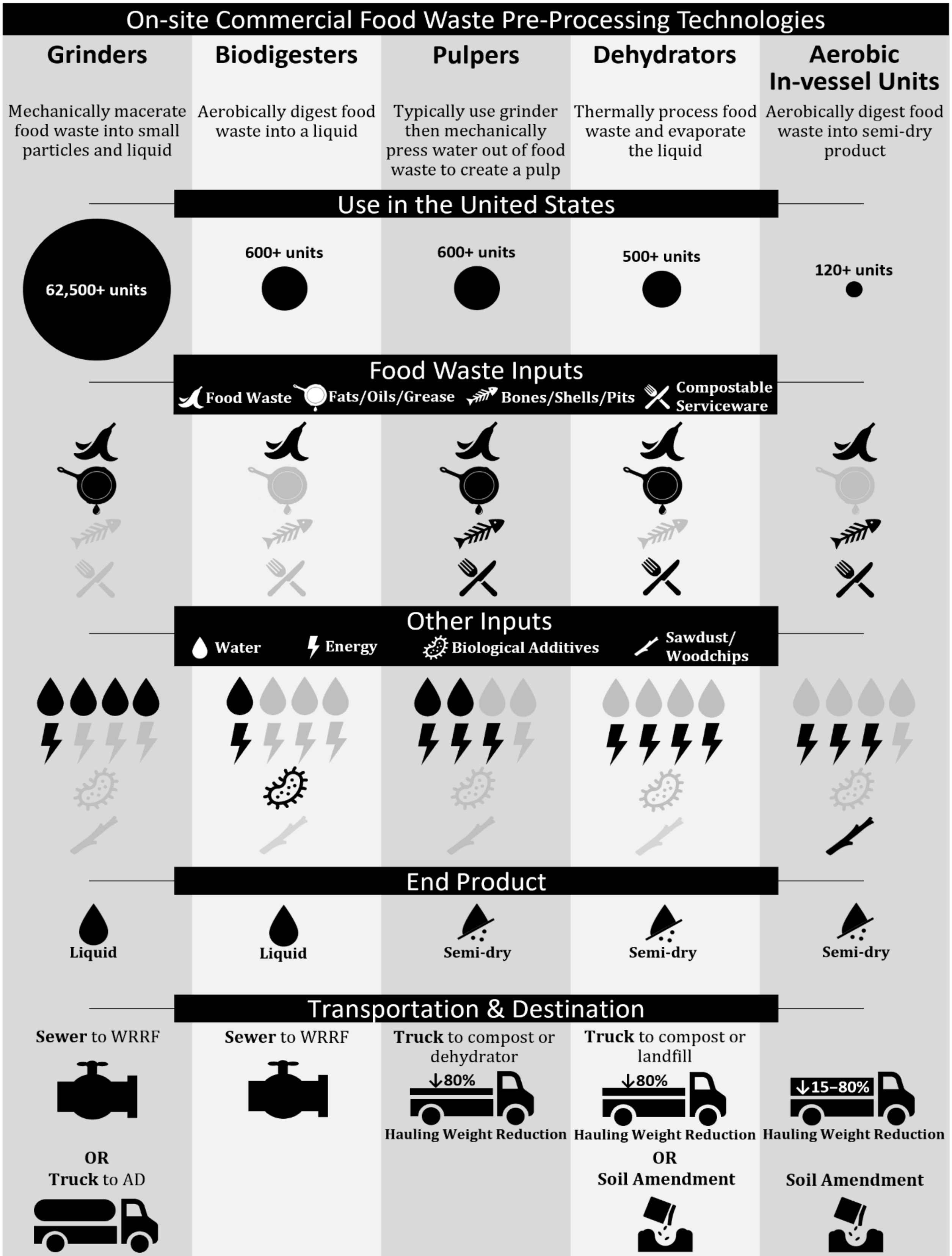


FIGURE 1. COMPARISON OF ON-SITE COMMERCIAL FOOD WASTE PRE-PROCESSING TECHNOLOGIES

WRRF = wastewater resource recovery facility; AD = anaerobic digestion

1.2. Scope and Methods

Various brands and models of each type of commercial food waste pre-processing technology are discussed; however, all models and brands are not necessarily included in this paper. In addition, several classes of technology were considered outside the scope of this paper and thus excluded, such as:

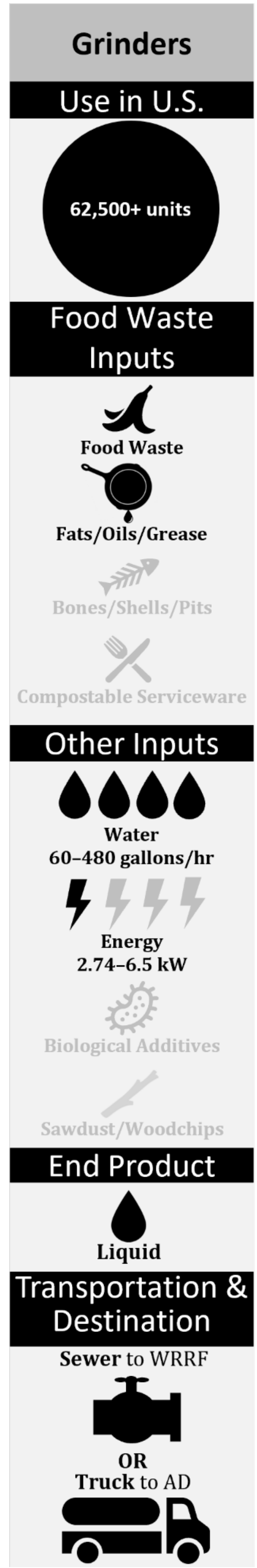
- Smaller, decentralized versions of traditional food waste pathways, such as composting (e.g., the Susteca AB Big Hanna, Wakan Environment Inc. CITYPOD, Jora Tumbler, and NATh Sustainable HotRot) and anaerobic digestion (e.g., SEaB Energy, Impact Bioenergy, and Living Arts Systems);
- Technologies that separate organic waste from municipal solid waste (e.g., Anaergia Organics Extrusion Press) to enable processing at an AD facility;
- Technologies typically used by composting and AD facilities, farms, or food processing facilities, rather than consumer-facing businesses and institutions that generate food waste, including de-packagers[2] and technologies to process food waste prior to using it as animal feed.

This issue paper is based upon a review of available literature. Since very limited peer-reviewed research is available on this topic, the issue paper relies heavily on gray (non-peer-reviewed) literature, including the comprehensive overview of on-site systems published by RecyclingWorks Massachusetts (RecyclingWorksMA, 2018); the Composting Collaborative's Pretreatment Directory (The Composting Collaborative, 2020), which was funded in part by EPA; and the California Department of Resources Recycling and Recovery (CalRecycle) guidance documents (CalRecycle, 2020c, d). The issue paper also relies upon articles, case studies, and interviews from the organics recycling e-magazine *BioCycle*[3] (Coker, 2019; Goldstein and Dreizen, 2017; Coker, 2016; Goldstein, 2015; Neale, 2013; Sullivan, 2012) and shares information provided by the manufacturers or vendors themselves that has not been independently confirmed by peer-reviewed research. More detailed information on the literature search strategy can be found in Appendix A. Throughout the paper, metric tons are used to measure greenhouse gases and standard tons are used to measure food waste, unless otherwise noted.

[2] A discussion of de-packagers can be found in another EPA report in this series: "Emerging Issues in Food Waste Management: Plastic Contamination" (EPA 600-R-21-001, August 2021).

[3] In 2020 *BioCycle* transitioned from a print magazine to a weekly e-newsletter, *BioCycle CONNECT*, and a newly relaunched website, BioCycle.net.

2. GRINDERS



One of the simplest ways to mechanically reduce the volume of food waste is to grind it up into a slurry. Grinders are commercial-sized garbage disposal systems that macerate food waste into a liquid effluent that is typically disposed of directly down the drain into the municipal sewage system. It can also be captured and hauled to an AD facility (Neale, 2013). Grinders can be purchased as stand-alone units (Figure 2) or may be combined with other technologies (e.g., pulpers) into larger pre-processing systems. Grinders are one of the more popular pre-processing technologies chosen by commercial food waste generators, with tens of thousands of commercial grinders currently in use across the United States (RecyclingWorksMA, 2018; Wright and Jones, 2017).

Product information—including processing capacity, accepted inputs, water and energy usage, cost, and trends of use in the United States—is summarized for several types of grinders on the market in Table 1 (located at the end of Section 2).

Processing capacities of grinders range from 250 pounds of food waste per day to 5 tons of food waste per hour; however, these are all manufacturer claims and none of this information has been independently verified through peer-reviewed research. Manufacturers claim that grinder models that capture the slurry on-site for transport to an AD facility produce "significant volume reduction" though it is unclear what significant means in this case (InSinkErator, 2020).

FIGURE 2. SALVAJOR SCRAPMASTER GRINDER

Photo Credit: Salvajor (2018c)

2.1. Inputs

Grinders usually require three inputs: food waste, electricity, and water. In general, the systems summarized in Table 1 accept all solid or liquid organic waste (including fats, oils, and grease), but do not accept any inorganic waste like metal, plastic (e.g., food service ware[4] and packaging), or other trash. According to the manufacturers of the grinder models listed in Table 1, the units use 1 to 8 gallons of water per minute (it is unclear how many minutes the water typically runs). The energy usage was not reported by any of the manufacturers except Salvajor, whose various models require 2.74 to 6.5 kW electricity (it is unclear to which processing time this wattage applies). Estimates of resources required per ton of food waste processed are not available.

2.2. End Products

Grinders generally produce one end product, the slurry of ground-up food waste, and most grinder models send the slurry directly down the drain into the municipal sewage system. The fact that grinder output can be sent directly down the drain, without the need for storing, hauling, or other processing, makes grinders a popular choice for commercial facilities that generate large quantities of food waste (Wright and Jones, 2017).

Some models, like the InSinkErator Grind2Energy (Figure 3) and Landia Biochop, do not send the slurry down the drain but instead capture it in a large onsite holding tank (that can be stored outside) so a liquid waste hauler can pick up the slurry and transport to an AD facility for conversion to bioenergy (InSinkErator, 2020). These hauling-based grinders may present environmental advantages over their sewer-based counterparts. One study showed that hauling food waste slurry to an AD facility reduces GHG emissions and generates more biogas during AD compared to sending the slurry down the drain for AD at the wastewater resource recovery facility (WRRF) (Parry, 2012). This study is discussed more in Section 2.3.

FIGURE 3. INSINKERATOR GRIND2ENERGY GRINDER

Photo Credit: Emerson (2020)

[4] Service ware includes plates, serving trays, cups, utensils, and associated items.

2.3. Environmental Benefits and Impacts

Grinders raise multiple potential environmental concerns, most of which are associated with sending the pre-processed food waste down the drain. These factors are discussed in detail in Text Box 1, as they apply to all technologies that send food waste down the drain.

However, these technologies can also process food waste into a pumpable slurry that can be used by anaerobic digesters. Grinder models designed to capture effluent (rather than send it down the drain) so it can be hauled to an AD facility for conversion to bioenergy exhibit a different set of environmental impacts and benefits. A 2013 study published by Water Environment Research Foundation (WERF) (Parry, 2012)[5] conducted a life-cycle assessment (LCA) to compare the impacts of five different food waste management methods including two types of grinders: ones where effluent is sent down the drain, into the sewer, and on to a wastewater resource recovery facility[6] (WRRF) operating with AD; and ones that collect effluent for hauling to AD facility. The former focused on residential effluent, while the latter examined commercial effluent. The study also assessed collection and hauling of commercial food waste to a landfill, composting facility, and mixed materials recovery facility (MRF), where it is separated and then taken to either a landfill or AD facility. Vendor data was preferred source of information for the study, followed by literature and professional experience of author. The study was peer-reviewed, but funded by InSinkErator (Parry, 2013).

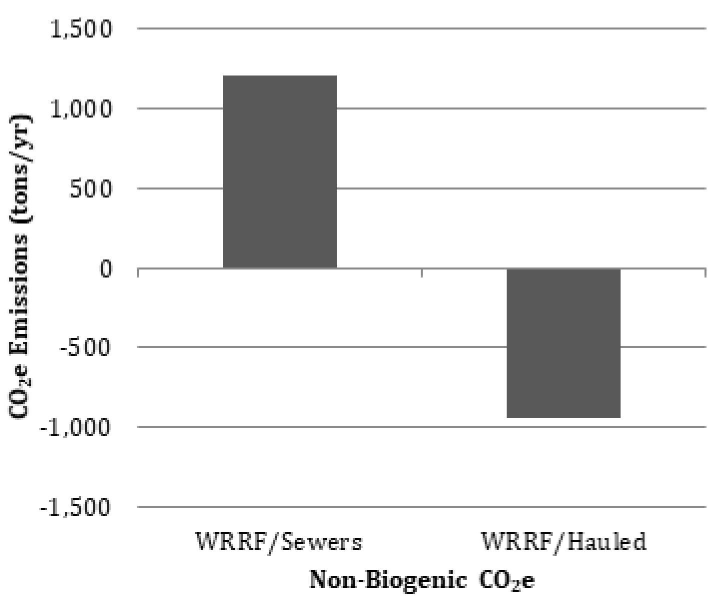


FIGURE 4. COMPARISON OF THE CARBON FOOTPRINT (IN CO_2e) FROM HAULING VS. SEWER TRANSPORT TO WRRF

Source: Parry (2012)

[5] Parry is the author of the WERF study referenced, thus the citation (Parry, 2012) does not include WERF.

[6] This report uses the term wastewater resource recovery facility (WRRF) in lieu of the term wastewater treatment plant (WWTP) used in some source material to highlight the potential for recycling by the facilities.

The WERF study found that hauling liquified food waste by truck and processing it via AD yields lower GHG emissions (measured as carbon dioxide equivalent, CO_2e) than sending liquefied food waste down the drain, through the sewer, and then processing it at a WRRF with AD (Figure 4). These lower emissions were primarily due to electricity generation from the biogas produced from AD (credit was given for avoided electricity generation by traditional means) and avoided fugitive emissions of methane in the sewer system.[7] When comparing the emissions of hauling food waste to a WRRF vs. sending it to a WRRF via the sewer, the author estimated that hauling via truck contributed to 60 CO_2e, while conveying the same amount of food waste to the WRRF via sewer contributed 1,100 CO2e of fugitive methane emissions (Parry, 2012). The author noted that little is known about the anaerobic decomposition rate of food waste in the sewer system and assumed a degradation rate of 15 percent in their study (Parry, 2012). The study found that conveying food waste via sewer and processing it at a WRRF with AD yielded higher GHG emissions than composting, but lower GHG emissions than landfilling.

The WERF study also found that hauling and direct addition of food waste slurry to a WRRF's AD also yielded more biogas production than sending the liquified food waste through the sewer system to the WRRF's AD due to low efficiency in capturing food waste in the primary stages of wastewater treatment (Wright and Jones, 2017; Parry, 2012).

The California State Water Resource Board found similar results in their co-digestion capacity analysis: they estimated that co-digestion of food waste in a WRRF (transported there via hauling) leads to a net emissions reduction factor of 0.65 to 0.70 metric tons CO2 per wet ton of food waste, as compared to landfilling (SWRCB, 2019). Both studies indicate the emissions associated with hauling food waste by truck are not significant compared to potential GHG benefits of producing bioenergy. A comparison of the net environmental value of sending a commercial (not residential) food waste slurry through the sewer system to WRRF with AD with ending unprocessed food waste directly to AD facility is not available in the literature. However, this research indicates that hauling-based grinders may have environmental advantages over their sewer-based counterparts.

[7] These two factors account for the negative total emissions of food waste hauled to WRRF with AD in the study.

TEXT BOX 1. POTENTIAL CONCERNS WITH SENDING PRE-PROCESSED FOOD WASTE DOWN THE DRAIN

Most grinders and biodigesters produce a liquid end product meant to simply be sent down the drain, into the sewer system, and to the WRRF. By doing so, businesses and institutions can save money by avoiding hauling and landfill tipping fees. Also, storage space is not required, as with methods that require hauling. Businesses may also choose these technologies to be more environmentally sustainable by avoiding the GHG emissions associated with hauling and landfilling food waste, or, in some states and localities, to help them comply with organic waste laws. However, numerous concerns arise when additional organic waste is added to the sewer and wastewater treatment systems, especially if commercial food waste generators in a particular area more broadly adopt grinders and/or biodigesters. Many of these concerns have not yet been quantified in the scientific literature, and additional research in these areas is warranted. Here two kinds of concerns are discussed – environmental and operational.

Potential environmental concerns:

- ***Fugitive methane emissions.*** As food waste travels through the sewer system and continues to break down, it may generate methane emissions. A 2012 study by the Water Environment Research Foundation (WERF) noted that little is known about the anaerobic decomposition rate of food waste in the sewer system, and assumed a degradation rate of 15 percent in the sewer system in their research (Parry, 2012).

- ***Loss of biogas potential.*** Food waste may also lose some of its energy potential (i.e., the potential to create biogas through anaerobic digestion) as it moves through the sewer system and continues to break down through the various stages of wastewater treatment before it reaches the anaerobic digester in the WRRF. This may be exacerbated by digesting the food waste in a biodigester before releasing it into the sewer system.

- ***Energy use in pumping systems.*** Transporting the slurry through sewer systems that use pumping stations (versus gravity-based systems) may require increased energy use.

- ***WRRFs without anaerobic digestion.*** The liquid output of grinders and biodigesters can only be recycled to produce biogas and biosolids if the receiving WRRF has AD capabilities. However, currently only one out of three WRRFs, representing approximately 3.4 million tons per year of available food waste processing capacity, have AD (U.S. EPA, 2021; Wright and Jones, 2017).

- ***Final destination for end products.*** While businesses may intend these technologies to divert food waste from landfills (and thus avoid the associated GHG emissions), that diversion is dependent on subsequent constraints and decisions by the receiving WRRF. The food waste may still ultimately reach a landfill or incinerator after pre-processing. Once the waste is processed via anaerobic digestion at the WRRF, the resulting biosolids may be landfilled rather than recycled, due to characteristics of sewage sludge, with which it is co-digested at the WRRF. (This issue arises regardless of whether food waste is sent down the drain or hauled to WRRF AD.) EPA survey data from 2017 and 2018 found that 18 percent of WRRFs landfilled biosolids, while 13 percent land applied biosolids (U.S. EPA, 2021, 2019, 2018). Biosolids can be applied as alternative daily cover at landfills, and it is unclear whether survey responders classified this activity as "landfilled" or "land applied." Biosolids may be landfilled for several reasons, including cost (landfill tipping fees may be the cheapest option), odor, public opposition, or high concentrations of metals or other toxins (from non-food materials).

continued on next page

Potential operational difficulties and costs:

- ***Additional treatment requirements.*** Liquified food waste often contains high levels of total suspended solids (TSS), biological oxygen demand (BOD), and fats, oils, and grease (FOG) (Dorsey and Rasmussen, 2012). One case study (Loyola Marymount University's dining hall) measured pollutants in biodigester effluent and found higher BOD, TSS, and FOG levels than are typically found in domestic raw sewage (Dorsey and Rasmussen, 2012). The study also found high levels of nitrates, phosphates, and pathogen indicators in the effluent (Wright and Jones, 2017). This additional pollution load could strain WRRFs, increasing the cost and energy required to process and treat wastewater. In addition, smaller WRRFs or WRRFs with small pipe sizes may not have sufficient capacity to accommodate significant increases in organic load (Wright and Jones, 2017).

- ***Pipe corrosion.*** Effluent with high BOD content may interact with sulfates that are normally produced in the human digestive tract (that subsequently enter the sewage system through toilet flushing) and produce hydrogen sulfide. Hydrogen sulfide can convert to sulfuric acid which corrodes pipes (CalRecycle, 2020d). Municipalities with small or aging pipes are particularly vulnerable to the risks of corrosion (Neale, 2013).

- ***Clogs and slugs.*** A portion of the effluent from pre-processing technologies that accept FOG may create clogs in the sewage system called "slugs" (CalRecycle, 2020d; Neale, 2013). Some WRRF operators hypothesize that food waste simply re-congeals further downstream in the sewage system to create slugs (Neale, 2013). Slugs can be challenging for municipal wastewater managers to detect until they are very large and difficult to remove (CalRecycle, 2020d). In a 2004 Report to Congress, EPA identified that 74 percent of sanitary sewer overflows were caused by blockages and 47 percent of the blockages were due to grease (U.S. EPA, 2004). Several studies show that removing FOG from the sewer systems and hauling it directly to a WRRF's anaerobic digester reduced sewer blockages and operating costs (Parry, 2014).

- ***Combined or "low flow" systems.*** There may be complications with sending additional food down the drain in "low flow" water systems or combined systems that could discharge during heavy rains. Where combined sewer outfall (i.e., one pipe transports rainwater runoff, domestic sewage, and industrial wastewater) exists, increased food waste being discharged into the sewer could increase the organic pollutant load of direct discharge into surface waters (Neale, 2013).

- ***Contamination.*** If small pieces of inorganic waste items from the food waste stream, like particles of plastic, glass, or metal packaging or service ware, pass through the grinder, this inorganic waste could be ground up along with the food waste and sent into the municipal sewage system. "Chips" or other inputs provided by vendors are also entering the sewer system, likely in disintegrated form. Persistent chemicals, such as per- and polyfluoroalkyl substances (PFAS), in food waste are also an emerging concern. However, no information was found in the literature about potential contaminants in grinder slurry or how well users separate inorganic materials from food waste before using the grinding systems.

TABLE 1. COMPARISON OF VARIOUS ON-SITE GRINDERS

Brand of Grinder	Description	Use in the U.S.[a]	Accepted Inputs from the Food Waste Stream	Other Inputs	Transportation and Destination	Unit Costs[b]	References (Non-Peer Reviewed and Manufacturer Data)
InSinkErator Grind2Energy	The InSinkErator grinds food waste into a slurry that is captured by an on-site holding tank.	NR	All food waste (including FOG); does not accept any nonorganic waste.	Water: 1–2 gallons/minute Energy: NR Processing capacity: 1 ton/hour	Hauled by truck to AD facility	NR	InSinkErator (2020); RecyclingWorksMA (2018); Rulseh (2016)
Landia Biochop	The BioChop is a complete processing unit (tank, grinder, and automation) that mechanically macerates and liquefies the food wastes and by-products.	NR	All food waste (including FOG); can handle small amounts of nonorganic waste	Water: Depends on feedstock, but generally not required Energy: Depends on feedstock and volumes Processing capacity: Up to 5 tons/hour	Hauled by truck to AD facility	$30,000–200,000	Landia (2020); Voell (2020)
Salvajor Food Waste Disposer	The Food Waste Disposer is commercial garbage disposal system that grinds food waste into a slurry that is pumped down the drain.	60,000	All organic waste; does not accept trash, metal, and plastic.	Water: 5–8 gallons/minute Energy: 2.74–5 kW[c] Processing capacity: 250–500 lbs/day	Sewer to WRRF	$4,000–6,000	RecyclingWorksMA (2018); Salvajor (2018a, 2018b)
Salvajor ScrapMaster	The ScrapMaster is a dish scraping station for large-scale kitchens. It includes a pre-flushing plume to rinse food waste off dishes, trays, and cookware, and a grinder that macerates the food waste into a slurry before it is sent down the drain.	2,500	All organic waste; does not accept trash, metal, and plastic.	Water: 7 gallons/minute Energy: 6.5 kW[c] Processing capacity: 750 lbs/day	Sewer to WRRF	$17,000	RecyclingWorksMA (2018); Salvajor (2018d)

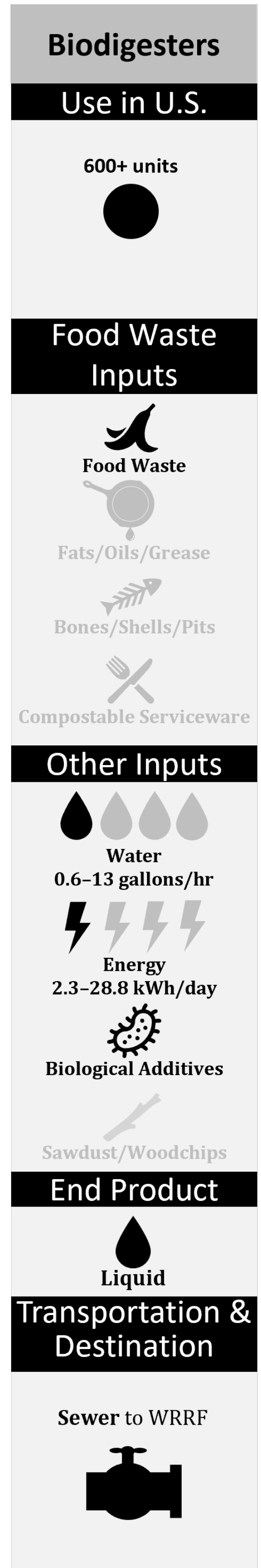
FOG = fats, oils, and grease; NR = information was not reported.
[a] This column includes the number of systems installed in the U.S. This information was current as of 2018 (RecyclingWorksMA, 2018).
[b] The unit costs in this column are only the cost of purchasing the equipment noted. There are additional costs for installation, maintenance, and any additional material required. The dollar year of the costs were not provided in the literature, but the date of the source's publication is noted in the references column.
[c] The time period or volume of food waste this energy use applies to was not reported

3. BIODIGESTERS

Biodigesters, also referred to as digesters, kitchen digesters, aerobic digesters, liquefiers, or “wet systems” (CalRecycle, 2020d), use aerobic digestion to break down food waste into a liquid within 24 hours. The resulting liquid is then disposed of down the drain directly into the existing municipal sewage system.[8] This method contrasts with that used by grinders that simply macerate food waste into a slurry of smaller particles before going down the drain into the sewer system (or being hauled to an AD unit). In the aerobic digestion process, biological additives (typically microorganisms) fueled by the presence of oxygen produce enzymes that subsequently break down and decompose the organic material at an accelerated rate.

Biodigester systems provide an optimal environment for this natural digestion process to occur and typically use a mechanized aeration technology, like a turner, agitator, or paddle arms, to ensure an oxygen-rich environment is maintained. Some include a built-in grinder or shredder (USCC, 2018). Incremental amounts of fresh water are also added to the system, and within 24 hours, the food waste is converted to liquid. This liquid output then typically passes through a screen and is disposed of directly into the municipal sewage system. Biodigesters are continuous feed systems so food waste can be added at any point if there is still room (Neale, 2013). Other benefits of biodigesters are the reduction of odors, reduction of pests (like rodents and insects), and increased sanitation due to the enclosed processing vessels that are normally associated with storing food waste until it can be hauled away (USCC, 2018). An ideal place to install a biodigester in a commercial kitchen is near the food preparation or dishwashing station (Figure 5) (Goldstein and Dreizen, 2017).

There are multiple biodigesters on the market in the United States. Their product information is summarized in Table 2 (located at the end of Section 3). The biodigester brands described in Table 2 all work very similarly; the main differences are the type of biological additives required and the volume of food waste they can process (Neale, 2013). The processing capacities of the biodigesters in Table 2 range from 45 to 2,400 pounds of food waste per day; however, none of these values have been independently verified through peer-reviewed research. The biodigesters all come equipped with analytics technology and scales to help food waste generators understand the quantities and types of food waste they generate (BioHiTech, 2020; ORCA, 2020a). While fewer biodigesters than grinders are in use in the United States currently, the adoption of biodigesters grew in the last decade across the country.



[8] While hauling the biodigester output via truck to an AD facility may be feasible, there was no mention of this option in practice in the literature.

FIGURE 5. POWER KNOT LFC-70 BIODIGESTER, FUJITSU CAMPUS CAFETERIA, SUNNYVALE, CALIFORNIA

Photo Credit: Power Knot LLC (2019)

A few case studies on biodigesters are available in the gray literature. In Sunnyvale, California, the Fujitsu company’s campus uses a Power Knot Liquid Food Composter[9] system in the preparation area of their cafeteria kitchen, which typically generates approximately 100 pounds/day of pre-consumer food waste (Neale, 2014). Fujitsu said its biodigester reduced its trash pick-up from daily to only 3 days a week, leading to a payback period of 18 to 20 months on the $18,000 system (Neale, 2014). The Boston Marriott hotel in Quincy, Massachusetts, installed a BioHiTech biodigester in its kitchen, near the dishwashing area, to help process the approximately 800 pounds of food waste it was generating daily. Originally, the hotel had a hauler collect unprocessed food waste and transport it to a local composting facility six times a week, and using the biodigester instead led to both “financial savings and logistical simplicity” (Neale, 2014).

3.1. Inputs

Biodigesters require four inputs: food waste, biological additives, water, and electricity. The biodigester systems summarized in Table 2 generally accept all food waste except large bones, hard shells (like clam or mussel shells), and grease or fat. They do not accept any nonorganic waste like plastics and metal. While the BioHiTech systems accept liquid food waste, the ORCA systems do not.[10] Biological additives are also required to accelerate the aerobic digestion process in each system. All brands of biodigesters use their own proprietary mix of microorganisms and/or enzymes. Vendors charge for the biological additives, which are added at intervals ranging from continuously to once every 3 to 4 months (Neale, 2013). At least two vendors (ORCA and Power Knot) require the addition of media called “chips” that house their blend of microorganisms. It is unclear from the literature what these chips are made of and their fate.

Biodigesters require a continuous supply of fresh water pumped into the system to clean out the digestion vessel and replenish the water lost when the liquid is discharged into the sewer system (CalRecycle, 2020d). The water usage for the various brands of biodigesters (see Table 2) ranges from 30 to 500 gallons per day depending on

[9] Though the Power Knot Liquid Food Composter contains “composter” in its name, it is a biodigester, not a composter.

[10] A reason was not provided in the available literature.

the processing capacity of the unit. Estimates suggest that approximately 1 gallon of water is used for every 1 to 4 pounds of food waste processed (Neale, 2013). Electricity is also required to power each biodigester unit; the energy usage across brands ranges from 2.3 to 28.8 kWh of electricity per day. Estimates of resources required per ton of food waste processed are not available.

3.2. End Products

Biodigesters produce one end product: a filtered and liquified food waste.[11] Biodigesters are connected directly to a drain so the liquid output can be sent into the municipal sewage system from which it will ultimately end up in a WRRF; the environmental impacts of this process are discussed in Text Box 1 and Section 3.3. Many biodigester companies describe their technologies as “waste to water,” however the liquid produced by biodigesters is categorically wastewater and not clean water (Neale, 2013). Other companies describe the organic liquid output as graywater, a term normally used to describe the drainage water from on-site systems like bathtubs, showers, sinks, and washing machines (CalRecycle, 2020d; Neale, 2013). However, graywater is typically clear in appearance and has a low turbidity, whereas the output from the biodigester systems is not (CalRecycle, 2020d).

FIGURE 6. LIQUEFIED FOOD WASTE OUTPUT FROM A BIODIGESTER ENTERING THE SEWER SYSTEM

Source: Rasmussen (2012)

[11] Technically biodigesters convert 99 percent (not 100 percent) food waste into the liquefied stream. The available literature does not provide an explanation; however, the Author supposes the 1 percent is likely solids captured by the filtering screen before waste enters the sewage system and that the 1 percent may be ultimately landfilled or incinerated.

3.3. Environmental Benefits and Impacts

Biodigesters have both environmental benefits and impacts that are not quantitatively characterized in the literature. Many of these factors are associated with sending the effluent down the drain. Those factors are discussed in detail in Text Box 1. While biodigester companies describe their outputs as “a complete diversion from landfill” (BioHiTech, 2020) and an “100% recycling solution” (ORCA, 2020b), these claims are improbable. Independent research is needed to quantify biodigester output that is ultimately being recycled compared with output that is being landfilled when it reaches a WRRF.

Unlike grinders, biodigesters may lower the BOD of food waste prior to release into the sewer thus reducing extra strain on the WRRF, according to manufacturers (BioHiTech, 2020; ORCA, 2020a). However, the liquid output from biodigesters reportedly still has relatively high levels of BOD in comparison to raw sewage (CalRecycle, 2020a) – and biodigestion may lower the effluent’s biogas potential if receiving WRRF has AD. Furthermore, the effluent quality varies by what type of food is being processed and what biological supplements have been added to the system to aid the digestion process. For example, digested dough and dairy have higher BOD levels than digested vegetables (CalRecycle, 2020d). No peer-reviewed research currently clarifies which biological additives and which food types input into biodigesters produce a higher quality liquid effluent than others.

In addition to BOD, TSS, and FOG, liquified biodigester output also contains unbeneficial[12] bacteria. A case study of Loyola Marymount’s dining hall found that the total coliform and enterococci concentrations in the ORCA output were similar to what is typically found in low-strength domestic sewage (Dorsey and Rasmussen, 2012). While the gray literature indicates that biodigester output has high levels of unbeneficial bacteria, this contention has yet to be confirmed via peer-reviewed research.

Another environmental quality consideration is the amount of electricity and fresh water required to operate the biodigester units. Biodigester units use approximately 20 to 500 gallons of water per day (though these data are unverified by independent research), which should be considered when weighing the environmental pros and cons of these systems (Neale, 2013). The amount of energy needed to power the system, treat the clean water added to the system, and ultimately treat the effluent in the WRRF are all associated with increased GHG emissions, not reductions (CalRecycle, 2020d). An independent, peer-reviewed LCA would be needed to compare the environmental impacts of sending pre-processed liquified food waste down the drain versus not pre-processing the food waste and hauling it straight to a landfill or centralized composting or AD facility.

An environmental benefit of biodigester systems is that many come equipped with scales and an integrated analytics tool to quantify the amount and type of food waste entering the unit. The data provide commercial and industrial food waste generators with a better understanding of which types of food are most often being wasted in their facilities and enable more informed decisions about which types of food to purchase, cook, or manufacture less of in the future to prevent food waste. Ultimately, this information can help businesses and institutions reduce food waste and costs.

[12] Meaning bacteria not intentionally added into the biodigester.

TEXT BOX 2. STATE AND LOCAL POLICIES REGARDING GRINDERS AND BIODIGESTERS

EPA's National Pretreatment Program provides the necessary regulatory tools and authority to states and localities to control pollutants that interfere with WRRF treatment processes, like FOG entering the sewer system from food service establishments (U.S. EPA, 2012). However, state and local governments vary in how they address liquefied food waste discharges into the sewer. The regulations and fees charged may be higher than for some other types of discharges, and some states, like California, recommend checking with local sewer districts and WRRFs to ensure liquefied food waste is suitable to enter the sewer system (CalRecycle, 2020d). However, due to the limited number of biodigesters in the U.S. and the fact that wastewater authorities have limited or generalized knowledge of these systems, few revised wastewater or plumbing guidelines and regulations apply specifically to biodigesters (Neale, 2013). Vendors may receive little oversight from state and local wastewater permitting authorities in the U.S. when they install these systems and may categorize the installation of a biodigester as a "replacement" of an existing plumbing fixture (e.g., a slop sink) that does not require state or local permitting (Neale, 2013). Unless specifically requested by a customer, vendors generally do not proactively contact local wastewater authorities to determine the acceptable discharge levels of BOD, TSS, and FOG (Neale, 2013). However, the pre-processing technology vendors and commercial food waste generators are both responsible for complying with existing regulations, like the National Pretreatment Program standards (U.S. EPA, 2012).

State and local governments with landfill food waste disposal bans or mandatory food waste recycling programs may encourage, actively or incidentally, the use of food waste pre-processing technologies. In some states, compliance can be achieved (e.g., lowering the amount of food waste sent to a landfill below a threshold) through the use of these technologies, while in other areas, such as Massachusetts, compliance can only be achieved with grinders or biodigesters if the wastewater utility receiving the waste approves it (Wright and Jones, 2017). In New York City, commercial grinders are banned. In California, biodigester effluent is not considered compliant with the state commercial organics law unless the entities in charge of the receiving sewage line and WRRF are notified and agree that the WRRF will actually recycle the liquified food (CalRecycle, 2020d).

TABLE 2. COMPARISON OF VARIOUS ON-SITE BIODIGESTERS

Brand of Biodigester	Description	Use in the U.S.[a]	Accepted Inputs from the Food Waste Stream	Other Inputs	Transportation and Destination	Unit Costs[b]	References (Non-Peer Reviewed and Manufacturer Data)
BioHiTech America Digesters	BioHiTech digesters use aerobic digestion and a blend of microorganisms to break down food waste into a liquid form within 24 hours. They can process most food items without grinding or other pre-processing required. The manufacturer claims that once the food waste is completely broken down, it is discharged as wastewater through any standard sewer line.	400+	Meat, seafood, poultry, produce, dairy, liquids, prepared foods, grains, breads, and pastries; do not accept large bones, fat trimmings, clam or mussel shells, bread dough, packaging, paper, or chemicals.	Water: 15–150 gallons/day Energy: 2.5–13.3 kWh/day[c] Biological additives Processing capacity: 500–2,400 lbs/day	Sewer to WRRF	~$10,000–50,000[d]	BioHiTech (2020); The Composting Collaborative (2020); RecyclingWorksMA (2018)
ORCA EcoWaste Digester	The ORCA digesters use aerobic digestion, a proprietary blend of microorganisms, and "ORCA Biochips" (to serve as a substrate for the microorganisms) to decompose food waste into a liquid for discharge into the municipal wastewater system within 24 hours.	79	Food waste including chicken bones, egg shells, meat, fish, and bread; do not accept large bones, liquids, grease, coffee grinds, and inorganic waste like paper, plastics, and metal	Water: 30–150 gallons/day Energy: 10.32–28.8 kWh/day Biological additives Processing capacity: 250–2,500 lbs/day	Sewer to WRRF	$10,000–$50,000	ORCA (2020a); The Composting Collaborative (2020); RecyclingWorksMA (2018)
Power Knot Liquid Food Composter (LFC) Biodigesters	The LFC biodigesters use aerobic digestion, a proprietary blend of microorganisms and enzymes (Powerzymes), a proprietary medium called Powerchips that houses the Powerzymes, and a rotating arm to liquify food waste within 24 hours. The digestion is a continuous process so food waste can be added at any time and all units connect to the cloud to provide users with statistics on the weight of the input waste and usage. Power Knot has a range of eight sizes of varying processing capacities to meet the differing needs of users.	Hundreds	"Anything you can eat," including fruits, vegetables, meat, fish, cheese, bread, eggshells, and lobster and shrimp shells; do not accept large meat bones, fruit pits, and oyster shells.	Water: 14–320 gallons/day[e] Energy: 2.3–25.3 kWh/day Biological additives Processing capacity: 45–2,200 lbs/hr	Sewer to WRRF	$10,000–$250,000	Power Knot (2020); The Composting Collaborative (2020); RecyclingWorksMA (2018)

FOG = fats, oils, and grease; NR = information was not reported.

[a] This column includes the number of systems installed in the U.S. This information was current as of 2018 (RecyclingWorksMA, 2018).

[b] The unit costs in this column are only the cost of purchasing the equipment noted. There are additional costs for installation, maintenance, and any additional material required. The dollar year of the costs were not provided in the literature, but the date of the source's publication is noted in the references column.

[c] Converted from 75–400 kWh/month to 2.5–13.3 kWh/day (conversion factor = 1 month/30 days).

[d] Pricing information for the largest model (the Sequoia) was not found; a previous version of the BioHiTech biodigester with similar processing capacity (2,400 lbs/day) cost $25,000–50,000.

[e] Water usage information was not found for the largest model, the Power Knot LCF-1000.

4. PULPERS

One of the simplest ways to reduce the volume of food waste is to mechanically press the liquid component out of food waste using a pulper, also referred to as a press or dewaterer. A pulper creates a semi-dry end product. Pulpers usually include (or are paired with) grinders (Figure 7) so that the incoming food waste is first mixed with water and macerated before the pulper squeezes out excess water. Table 3 provides product information for two available brands of pulpers. As of 2018, over 600 Somat pulping systems were in use in the United States (no data was available for other pulper brands).

FIGURE 7. SOMAT SPC-50S PULPING SYSTEM WITH GRINDER

Photo Credit: Somat (2018a)

Metro Vancouver[13] (2014) reviewed dewatering technologies and found that the main benefits of these systems are that they can rapidly reduce the volume of food waste, and materials can be continuously processed instead of processed in batches. Additionally, the labor requirements of running the machine are minimal and the units are compact and can be installed in small kitchen areas (if electrical and drainage connections are available).

Pulpers

Use in U.S.

600+ units

Food Waste Inputs

Food Waste

Fats/Oils/Grease

Bones/Shells/Pits

Compostable Serviceware

Other Inputs

Water
60–180 gallons/hr

Energy
402 kWh/day

Biological Additives

Sawdust/Woodchips

End Product

Semi-dry

Transportation & Destination

Truck to compost or dehydrator

↓80%

Hauling Weight Reduction

[13] Metro Vancouver is a federation of 21 municipalities, one Electoral Area and one Treaty First Nation that collaboratively plans for and delivers regional-scale services. They are governed by a Board of Directors of elected officials from each local authority. Core services include drinking water, wastewater treatment and solid waste management.

4.1. Inputs

Pulpers require three inputs: food waste, electricity, and water. While pulpers dewater food waste, the systems also need additional water to help mix the food waste input in the unit prior to dewatering. They accept all solid or liquid organic waste (including FOG) in addition to compostable service ware and napkins but do not accept inorganic waste like glass, metal, wood, and fabric. The water and energy usages for pulpers are claimed to be 60 to 180 gallons of water per hour and 16.75 kWh per hour (energy data for Somat models only) though no independent research has confirmed these values. Estimates of resources required per ton of food waste processed are not available. Metro Vancouver (2014) found the biggest negatives of the dewatering systems are the water and energy usage required to run the machines.

4.2. End Products

Pulpers produce two end products: a semi-dry food waste pulp and excess water removed during the pulping process. The semi-dry pulp is typically sent to a composting facility or for further processing in a dehydrator system (see Section 5) to remove additional water (Somat, 2018a, b). The excess water that is extracted from the system is either sent down the drain or, in some brands like the Somat, first reused to help flush the feeding tray or trough (RecyclingWorksMA, 2018).

4.3. Environmental Benefits and Impacts

Pulpers require natural resources, namely water and energy, to operate. One of the most significant environmental benefits of pulpers is that they produce a pulp that can be processed into compost at a centralized facility. Because pulpers purportedly reduce the volume and weight of commercial food waste by approximately 85 to 87.5 percent, pulpers help reduce the GHG emissions and fuel use associated with hauling food waste via truck to composting facilities or landfills. No data were found on the magnitude of emissions reduced by pulpers that divert food waste from landfill and decrease fuel use associated with transporting the waste. Whether composters may need to add water back to the pulped waste to achieve optimal conditions for composting is not discussed in the literature, and this could be cause for concern in areas where water is scarce. An LCA would be needed to compare the environmental impacts of pulping versus not pulping food waste before sending it to a composting facility or a landfill.

TABLE 3. COMPARISON OF VARIOUS ON-SITE PULPERS

Brand of Pulper	Description	Use in the U.S.[a]	Accepted Inputs from the Food Waste Stream	Other Inputs	Transportation and Destination	Unit Costs[b]	References (Non-Peer Reviewed and Manufacturer Data)
InSinkErator WasteXpress	The WasteXpress grinds food waste into a slurry that is fed into a dewatering press. The dewatered pulp is discharged into a ten-gallon bin and the captured water is sent down the drain.	NR	Liquid and solid food waste, napkins	Water: 120–180 gallons/hour[c] Energy: NR Processing capacity: 700 lbs/hr	Truck to compost facility (hauling weight reduced 85%), or Dehydrator	NR	Emerson (2016)
Somat Close Coupled Pulpers	Somat pulpers, which come in two unit sizes, mix commercial food waste with water and grind it into a slurry that is fed into a dewatering press (called the Hydra-Extractor) to produce a semi-dry pulp.	600+	All liquid and solid food waste and compostable trays, cups, and plasticware; does not accept glass, china, metal, stoneware, wood, and towels.	Water: 60–120 gallons/hour Energy: 16.75 kWh/hour Processing capacity: 900–1,250 lbs/hr	Truck to compost facility (hauling weight reduced 87.5%), or Dehydrator	$53,000–$59,000	RecyclingWorksMA (2018); Somat (2018a, 2018b)

FOG = fats, oils, and grease; NR = information was not reported.

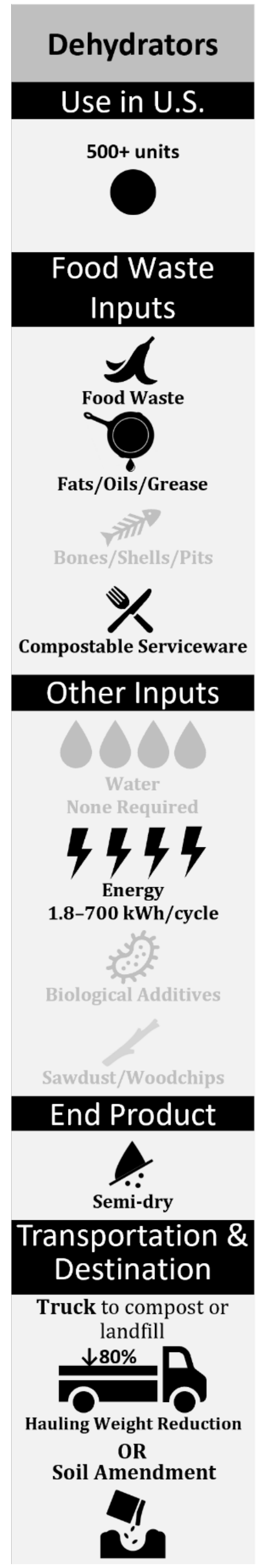
[a] This column includes the number of systems installed in the U.S. This information was current as of 2018 (RecyclingWorksMA, 2018).

[b] The unit costs in this column are only the cost of purchasing the equipment noted. There are additional costs for installation, maintenance, and any additional material required. The dollar year of the costs were not provided in the literature, but the date of the source's publication is noted in the references column.

[c] Converted from 2–3 gallons/minute to 120–180 gallons/hour (conversion factor = 60 minutes/1 hour).

5. DEHYDRATORS

Dehydrators transform commercial food waste into a dry end product. Instead of mechanically dewatering food waste like pulpers, dehydrators, also called “dry systems,” use heat to process food waste and evaporate the liquid component to create a dry biomass that, after further processing and/or curing, can be used as a soil amendment, plant fertilizer, or animal feed (CalRecycle, 2020c; Goldstein and Dreizen, 2017; Neale, 2013). The evaporate captured by the system is typically condensed and then sent down the drain into a municipal sewage system.



Dehydrators often include paddles, agitators, or grinders to stir and macerate the food waste; they either include a pulper in the unit itself or are preceded by a stand-alone pulper that pre-processes the dehydrator input (USCC, 2018; Neale, 2013). Dehydrators are typically placed near the food preparation area in kitchens (CalRecycle, 2020c). Manufacturers recommend that locations with higher volumes of food waste, like college cafeterias, separately pulp their food waste first and then put it into the dehydrator unit to achieve the greatest volume and weight reduction possible (Neale, 2013). Because dehydrators are batch systems, not continuous feed systems (except for the GAIA models discussed below), users may need to temporarily store a large amount of food waste while the cycle finishes for each batch, which might be unfeasible for some potential users.

Product information is summarized in Table 4 for four of the most established dehydrator brands on the market. Overall, the different brands have similar operations: they heat food waste to evaporate the moisture and agitate it until the cycle is complete, leaving a pulpy mass of dried food waste (CalRecycle, 2020c). Another type of dehydrator system briefly mentioned in the literature is the BioGreen Hybrid system. It combines operating elements of biodigesters with dehydrators to produce dried organic pellets (Neale, 2013); however, no further information on this hybrid unit could be found. The processing capacities of the dehydrators on the market range from 66 to 3,300 pounds of food waste per cycle (cycles range from 8 to 22 hours) and reduce the volume and weight of food waste by 80 to 93 percent, though these specifications remain unverified through independent research. Several hundred food waste dehydrators are operating in the United States (Table 4). No information was found on expected trends in the adoption of these systems in the future.

Metro Vancouver (2014) reviewed dehydrator technologies and found the main benefit of these systems are that they provide a relatively inexpensive way to greatly reduce the volume of food waste, with the downside that the end product requires further processing before it can be used as a soil amendment. The systems are relatively small and require little labor (i.e., users can “set and forget” until the cycle finishes running), but interim storage is needed to store newly-generated food waste while a batch is running (Metro Vancouver, 2014). A potential solution to avoid interim storage is the use of two dehydrator units, though this may not be a viable option for some commercial food waste generators (e.g., due to additional expenses and space requirements). Another disadvantage of these systems is the high energy use required to evaporate moisture (Metro Vancouver, 2014).

There are a few case studies on dehydrators in the literature highlighting volume reduction and end uses. A 2-month pilot test of an EcoVim 250 dehydrator at a small Virginia prison demonstrated that the dehydrator converted 131 pounds of raw food waste into 30 pounds of dehydrated output, used 3 kw per hour (a cost of $4.50/day), and reduced the prison’s solid waste disposal from five bags per day to one bag per day (USCC, 2018). A large Hilton Head, South Carolina, resort uses three GAIA dehydrators to process 20 to 35 percent of its food waste and cures its dehydrator output in an aerobic in-vessel unit, and the end product is used as a soil amendment for the resort's landscaping (Kachook, 2018; USCC, 2018). In Montville, Connecticut, Rand Whitney Recycling uses a GAIA 100 dehydrator at its large 7,500-person facility to reduce the large amount of food waste stored on their loading dock (which was leading to pest issues, including a mice and fruit fly infestation) (Neale, 2014). These systems were able to eliminate organics hauling costs and use the dehydrated waste as a small component (~1 percent) of the mulch and composting mix they use for the substantial landscaping at the facility (Neale, 2014). St. Cloud Hospital in St. Cloud, Minnesota, installed a pulper and two Somat dehydrators (Figure 8) that reduced the facility's approximately 1,800 pounds of food waste per day to one 30-gallon receptacle per week (Neale, 2014). In Figure 8, The dehydrator on the right has finished its cycle and is unloading the dehydrated food waste while the dehydrator on the left is being loaded from food waste that has been processed with a pulper first.

FIGURE 8. SOMAT DEHYDRATORS, ST. CLOUD HOSPITAL, MINNESOTA

Photo Credit: Somat (2014)

5.1. Inputs

Dehydrators require two inputs: food waste and energy. The dehydrator systems described in the previous section generally can process a mix of food waste (though the systems vary on their ability to process FOG). The exceptions are very hard food scraps, such as large bones, coconut shells, avocado pits, and clam/oyster shells. One case study found that husks and sugar/oil should also not be combined in a batch or molasses will be created, risking damage to the equipment (Kachook, 2018). The dehydrators can also process compostable service ware and small amounts of paper and uncoated cardboard. Inorganic waste, like glass, metal, plastic, cloth, and china, should not be included in the waste.

The energy required for the dehydrators to operate varies by model, ranging from 1.8 to 700 kWh of electricity per cycle (cycles range from 8 to 22 hours). GAIA also manufactures gas-powered dehydrators that claim to use approximately 8 to 55 Nm^3 of gas[14] per cycle. None of these energy use claims has been validated through independent peer-reviewed research. Estimates of resources required per ton of food waste processed are not available.

[14] Nm^3 is a normal cubic meter. It represents the quantity of dry natural gas that occupies one cubic meter under 0°C and an absolute pressure of 1.01325 bar.

5.2. End Products

Dehydrators produce two end products: dehydrated food waste and the reconstituted steam (i.e., condensate) removed by the dehydration process. The dehydrated food waste is intended for use as a soil amendment (typically after further processing) or composting feedstock, or it may ultimately be landfilled (CalRecycle, 2020c; Neale, 2013). Data was not available in the literature on prevalence of on-sire curing or of end use. The condensate produced by dehydrators is typically filtered and sent directly down the drain into a municipal sewage system.

Some dehydrator manufacturers claim their systems are “Food Waste In, Compost Out,” or “Food Waste In, Potable Water Out” (Neale, 2013), but the dry output is not stable enough to be used directly as a soil amendment. It requires a curing period or further processing in a composting facility before it is suitable for use as compost (CalRecycle, 2020c). Curing is the process of allowing the dehydrator output to continue to mature and fully decompose and stabilize over time (often a few weeks) to prevent odors, growth of large fungal colonies, and attraction of disease vectors (e.g., flies) (Neale, 2013; Rasmussen and Bergstrom, 2011).

Local and state regulations and policies should be consulted prior to land application to determine permissibility or compliance with applicable requirements. For example, California specifies that “dried food waste is not compost or a compost product” as dehydrators do not biologically decompose food waste into a stable substance (CalRecycle, 2020c). If the dried food waste becomes wet again, it can reabsorb water and regain similar characteristics to unprocessed food waste like odor and attracting vectors (CalRecycle, 2020c).

In one case study, Loyola Marymount University evaluated the suitability of its dining hall’s Somat dehydrator output for use as a landscaping soil amendment (Rasmussen and Bergstrom, 2011). The dehydrated food waste did not break down like normal compost and contained increased fungal growth (Figure 9) and attracted flies. Interviews performed by *BioCycle* indicate that fungal growth is influenced by the amount of moisture remaining in the dehydrated food waste after complete processing; the remaining moisture seems to vary from system to system (Neale, 2013). Overall, composters interviewed by *BioCycle* expressed they were satisfied with receiving dehydrated food waste as a composting feedstock due to the levels of valuable nutrients, like nitrogen and carbon, it contained (Neale, 2013).

FIGURE 9. INCREASED FUNGAL GROWTH OVER TIME ON DEHYDRATED FOOD WASTE

Photo Credit: Rasmussen (2012)

A recent peer-reviewed study assessed the potential end uses of dehydrated food waste. Schroeder et al. (2020) processed food waste streams from a variety of sources (including a restaurant, cafeteria, grocery store, hospital, and juice manufacturer) in an EcoVim-66 dehydrator. They analyzed the dehydrated food waste output and characterized it against several potential end uses, including use as fertilizer, composting feedstock, incineration feedstock, fish feed, cattle feed, and pelletized fuel[15] (Schroeder et al., 2020). Their results indicated that dehydrated food waste was not suitable for use directly as fertilizer due to low nutrient levels (across all food waste streams input into the system). However, they found that the dehydrated food waste was particularly suited for use as fish feed (due to a high protein content), as well as composting or pyrolysis[16] feedstock, pelletized fuel, and cattle feed. Ultimately, their analysis showed that the composition of the food waste stream should be matched to an end-use application for dehydration to be a worthwhile pre-processing strategy (Schroeder et al., 2020).

Regarding the dehydrator condensate, no studies confirm that it is potable as some manufacturers claim (Neale, 2013). For example, dehydrator condensate may contain BODs (Neale, 2013).

5.3. Environmental Benefits and Impacts

A significant environmental benefit of dehydration is that it converts food waste into a compostable pulp that can be cured and used as soil amendment or composting feedstock. Transportation of the pulp may still be needed if it is not cured or added to a composter on-site, but as dehydrators reduce the volume and weight of food waste by approximately 80 to 93 percent, emissions and fuel use associated with hauling are greatly reduced. No estimates were found on the magnitude of emissions saved by dehydrators that divert food waste from landfill and reduce fuel use associated with hauling.

Some environmental concerns regarding dehydrators require further research. BOD levels in the dehydrator condensate may be a concern, and the effects of the dehydrator wastewater streams on municipal sewage pipes and WRRFs are unknown. Additionally, dehydrators require a much larger amount of energy to operate compared with other types of pre-processing technologies. An LCA would be needed to compare the environmental impacts of dehydrating food waste and subsequently sending it to a centralized composting facility (or another destination, such as an AD facility or landfill) versus not dehydrating the food waste and hauling it straight to the intended destination.

[15] Pelletized fuel is a type of biofuel created from compressed organic matter or biomass, including food waste. The pellets are commonly burned as fuel for uses like commercial or residential heating, cooking, or power generation.

[16] Pyrolysis is a thermochemical process in which biomass material, like food waste, is heated to a high temperature in the absence of oxygen. One of the main products of pyrolysis is biochar, which is similar to charcoal and typically used as a soil amendment (Schroeder et al., 2020).

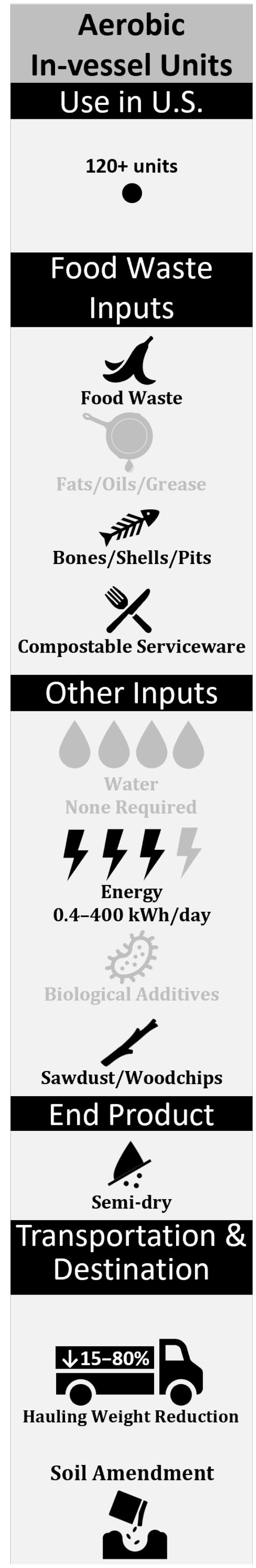
TABLE 4. COMPARISON OF VARIOUS ON-SITE DEHYDRATORS

Brand of Dehydrator	Description	Use in the U.S.[a]	Accepted Inputs from the Food Waste Stream	Other Inputs	Transportation and Destination	Unit Costs[b]	References (Non-Peer Reviewed and Manufacturer Data)
EcoVim Dehydrators	The EcoVim dehydrators use an internal decomposition chamber that is heated to 180°F to sterilize and evaporate the liquid in the batch of food waste placed into the system. The drying cycle is complete when a sensor detects a 0.01% moisture level. Six sizes of EcoVim dehydrators are available.	400+	Food waste and up to 15% paper and untreated cardboard per cycle; does not accept large bones, avocado pits, grease, and inorganic waste like metal, plastic, glass, or petrochemicals.	Water: Not required Energy: 1.8–10 kWh/cycle Processing capacity: 66–3,300 lbs/cycle (cycles last 8–22 hours)	Truck to compost facility (hauling weight reduced 80–90%), or Direct soil amendment[c], or Landfill	\$10,000–\$100,000+	The Composting Collaborative (2020); RecyclingWorksMA (2018); EcoVim (2015a, 2015b)
GAIA Dehydrators	GAIA dehydrators heat each batch of food waste to over 300°F, shred it with a built-in blade, and churn the food waste during a 10-hour cycle. The GAIA systems also include a blower chamber that allow additional food waste to be added while a cycle is running. The units are available in a variety of sizes and include both electric and gas models.	NR	Food waste and up to 10–15% compostable packaging per cycle; does not accept large bones, clam/oyster shells, avocado pits, FOG, and inorganic waste like silverware, cloth napkins, plastic, glass, or cans.	Water: Not required Energy: ~13–700 kWh/cycle (electric system) 8–55 Nm^3/cycle (gas system) Processing capacity: 250–2,500+ lbs/day (cycles last 10 hours)	Truck to compost facility (hauling weight reduced 85–93%), or Direct soil amendment[c], or Landfill	\$10,000–\$100,000+ (electric system) \$50,000–\$100,000+ (gas system)	The Composting Collaborative (2020)
Hungry Giant Food Waste Dry Dehydration System	The Hungry Giant system heats food waste to produce a semi-dry end product in 7–24 hours. The drying cycle is complete once the moisture sensor detects the food waste has reached a ~4–6% moisture level. The the captured steam is condensed and discharged down the drain.	NR	Food waste, paper, and paper napkins; does not accept plastics, metals, medicine, large bones, seafood shells, and crustaceans.	Water: Not required Energy: NR Processing capacity: NR (cycles last 8–22 hours)	Truck to compost facility (hauling weight reduced 80–93%), or Direct soil amendment[c], or Landfill	\$19,500–\$153,000[d]	LA County Public Works (2020); Hungry Giant Waste Technologies (2019)
Somat DH-100w Waste Dehydrator	The Somat DH-100w dehydrates commercial food waste by heating it to 180°F and mechanically agitating it with paddles until the dryness sensor stops the cycle. The captured steam condensate is discharged down the drain.	100+	All food waste and compostable service ware; does not accept any inorganic waste like glass, china, metal, stoneware, fabric, and plastic. Cardboard or leafy greens can be added to greasy batches to aid FOG absorption.	Water: Not required Energy: 3.0 kWh/cycle Processing capacity: 220 lbs/cycle (cycles last 14–16 hours)	Truck to compost facility (hauling weight reduced 83–93% alone, and 95% when paired with a pulper), or Direct soil amendment[c], or Landfill	~\$35,000	RecyclingWorksMA (2018); Somat (2017)

FOG = fats, oils, and grease; NR = information was not reported.
[a] This column includes the number of systems installed in the U.S. This information was current as of 2018 unless otherwise noted (RecyclingWorksMA, 2018).
[b] The unit costs in this column are only the cost of purchasing the equipment noted. There are additional costs for installation, maintenance, and any additional material required. The dollar year of the costs were not provided in the literature, but the date of the source's publication is noted in the reference column.
[c] Further curing or processing may be required before land application. [d]This price was current as of 2020 (LA County Public Works, 2020).

6. AEROBIC IN-VESSEL UNITS

Aerobic in-vessel units are a type of on-site food waste pre-processing technology that produce a semi-dry end product. Vendors also commonly refer to these units as in-vessel accelerated "composters," however they should not be confused with traditional composting systems, which have distinct composting and curing periods and produce stable, mature compost (USCC, 2018). Though the systems are often named "composters," the end product is not compost and requires further curing and maturation prior to use as a soil amendment. There are on-site in-vessel composting systems that do produce a stable compost (e.g., the Susteco AB Big Hanna, HotRot 1206, and Wakan Environmental Inc. CITYPOD) available to commercial food waste generators, but these processing technologies are outside of the scope of this paper and are not discussed (see Section 1.2 for a discussion of scope).



Aerobic in-vessel units typically comprise a rotating drum in which food waste (and other compostable material) is mixed with carbonaceous bulking amendments like woodchips or sawdust and aerobically decompose into a semi-dry end product using naturally occurring microorganisms. The systems control the moisture, oxygen level, and temperature inside the drum. Many of these units are very large, around the size of a shipping container (Figure 10), so are used by institutions with abundant space like universities and correctional facilities (Mendrey, 2013).

Product information for several aerobic in-vessel units is summarized in Table 5. Vendors of the rotary drum systems (e.g., the DT-Environmental EnviroDrum, FOR Solutions Composting Systems, and XACT Systems Bioreactor) claim that a semi-dry product is produced within 3 to 7 days, but that the product requires additional curing prior to use as a soil amendment. Other brands, like the Tidy Planet Rocket, take longer to process the food waste (~14 days) and require at least 2 to 3 weeks of curing prior to use. The in-vessel unit capacities range from 114 pounds to over 5 metric tons of food waste per day with a volume/weight reduction of 15 to 80 percent, depending on the type of food waste input. It is unclear if this volume/weight reduction excludes the weight of the bulking agent added. The units range in cost from $23,000 to $1,100,000. This higher end includes supplementary equipment options, for example, a pre-shredder or loading hopper. A little over a hundred systems appear to be in use across the United States.

A case study on Cedar Creek Correctional Facility near Olympia, Washington, was reported in *BioCycle* (Mendrey, 2013). The facility uses the DT-Environmental EnviroDrum (Figure 10) to process food waste along with wood chips and biosolids. The materials require approximately 3 to 5 days to pass through the rotating drum. The material is then unloaded, taken to a curing area, and cured for two to three weeks prior to use as a soil amendment. The facility noted that it took six to nine months to perfect the process due to difficulties maintaining a high enough temperature to reduce moisture content adequately (Mendrey, 2013). No problems were reported with the cured end product.

FIGURE 10. DT-ENVIRONMENTAL ENVIRODRUM AEROBIC IN-VESSEL UNIT

Photo Credit: DT-Environmental (n.d.)

6.1. Inputs

Aerobic in-vessel units require two inputs: food waste and a bulking amendment, like sawdust or woodchips (USCC, 2018; Goldstein and Dreizen, 2017). The amount of bulking amendment added depends on the amount and type of food waste being processed. The energy usage of the aerobic in-vessel units summarized in Table 5 varies greatly depending on the brand and unit size, using 0.4 to 400 kWh of electricity per day. No water is needed to operate the units. Estimates of resources required per ton of food waste processed are not available.

6.2. End Products

Aerobic in-vessel units produce a semi-dry end product that many vendors and manufacturers refer to as "compost" or "ready to use" (Goldstein and Dreizen, 2017). However, according to *BioCycle*'s research, only a few vendors of commercial aerobic in-vessel units produce finished compost that meets scientific standards for compost stability within 7 days (Goldstein and Dreizen, 2017). The end product of many of these machines is not mature or stable and has not fully gone through the natural aerobic decomposition process and the mesophilic and thermophilic stages of composting. Most vendors state they meet pathogen and vector reduction targets in the vessel but that additional curing is needed prior to use as soil amendment (Goldstein and Dreizen, 2017). Since curing is necessary, the user needs to have space, either on-site or off-site, to store the maturing material.[17]

6.3. Environmental Benefits and Impacts

Due to the very limited information in the literature about aerobic in-vessel units, the full span of environmental benefits and impacts that these systems have is unknown. The most significant environmental benefit appears to be that commercial food waste may be recycled (e.g., as a soil amendment) instead of landfilled. Because this technology reduces waste volume by as little as 15 percent, there may not be significant reductions in hauling emissions and fuel use if the output needs to be transported elsewhere. Additionally, the units require bulking amendments, like woodchips or sawdust, that must either be delivered or produced on-site. More research is

[17] While hauling the biodigester output via truck to an AD facility may be feasible, there was no mention of this option in practice in the literature.

needed to document these issues.

TABLE 5. COMPARISON OF VARIOUS ON-SITE AEROBIC IN-VESSEL UNITS

Brand of Aerobic In-vessel Unit	Description	Use in the U.S.[a]	Accepted Inputs from the Food Waste Stream	Other Inputs	Transportation and Destination	Unit Costs[b]	References (Non-Peer Reviewed and Manufacturer Data)
DT-Environmental EnviroDrum	The EnviroDrum mixes and aerates food waste and bulking agents (e.g., wood chips) with an auger within a rotating drum. A semi-dry end product is produced after 72 hours at 55°C. Four models are available that have various processing capacities.	100+	Food waste, manure, biosolids, green waste, paper, bioplastics; does not accept non-compostable materials in high concentrations	Water: Not required Energy: 25–400 kWh/day Sawdust or woodchips Processing capacity: 3–25 cubic yards/day	(hauling weight reduced 20–80%), or Direct soil amendment[c]	~$90,000–$350,000	RecyclingWorksMA (2018)
FOR Solutions Composting Systems	FOR Solutions Composting Systems are in-vessel rotary drum systems that produce a semi-dry end product in five days. Five models are available that have different processing capacities.	NR	Compostable materials (excluding FOG) and small amounts of paper packaging; does not accept non-compostables, glass, and metals	Water: Not required Energy: 23.85–65.33 kWh/day Sawdust or woodchips Processing capacity: 250–2,500 lbs/day	(hauling weight reduced 25%), or Direct soil amendment[c]	$100,000+	The Composting Collaborative (2020)
Tidy Planet Rocket Composter	The Rocket Composters are designed to process food wastes from food service or catering. The Rockets are continuous feed systems that produce uncured compost in 14 days, with an additional 2–3 weeks of curing required. There are six available unit sizes with different processing capacities.	20+	Cooked and uncooked meat, fish, fruit, and vegetables, garden waste, and animal waste; does not accept liquids or large bones	Water: Not required Energy: ~1.7–45 kWh/day Sawdust or woodchips Processing capacity: ~114 lbs/day–5 metric tons	(hauling weight reduced 50%), or Direct soil amendment[c]	$23,000–$1,100,000 (upper range includes supplemental equipment)	LA County Public Works (2020); Tidy Planet (2020); RecyclingWorksMA (2018)
XACT Systems BioReactor	The XACT BioReactor uses a slowly rotating drum and naturally occurring aerobic bacteria to decompose large volumes of food waste into a semi-dry end product in 4–7 days. The seven available unit sizes come with different processing capacities.	NR	Compostable materials, including paper packaging; does not accept metals, large bones, pits, waxed cardboard, non-compostable plastics	Water: Not required Energy: 0.4–4.5 kWh/day Sawdust or woodchips Processing capacity: 1,500–2,500+ lbs/day	(hauling weight reduced 15%), or Direct soil amendment[c]	$50,000–$100,000+	The Composting Collaborative (2020)

FOG = fats, oils, and grease; NR = information was not reported.

[a] This column includes the number of systems installed in the U.S. This information was current as of 2018 (RecyclingWorksMA, 2018).

[b] The unit costs in this column are only the cost of purchasing the equipment noted. There are additional costs for installation, maintenance, and any additional material required. The dollar year of the costs were not provided in the literature, but the date of the source's publication is noted in the references column.

[c] Further curing or processing may be required before land application

7. ANALYSIS OF ENVIRONMENTAL CONSIDERATIONS

This section synthesizes information from across the issue paper to address whether (and, if so, under what conditions) commercial food waste pre-processing technologies (a) enable or increase the recycling of food waste; and/or (b) reduce the overall environmental impact of food waste, and thus answer the paper's initial research questions. While almost no independent, peer-reviewed life cycle assessments have been performed on these technologies, many helpful insights exist in the literature. This section synthesizes the available data and presents relevant findings.

Do pre-processing technologies enable or increase the recycling of food waste?

Food waste can be recycled to produce biogas and/or soil amendments with or without pre-processing at the waste generation site, and the use of on-site pre-processing technologies does not guarantee recycling. However, all these technologies require source separation of food waste from inorganic waste, which is an important first step toward recycling. Once food waste is separated, food waste can be recycled on-site or hauled off-site to a composting, AD, or other recycling facility.

While businesses may use pre-processing technologies to divert food waste from landfills (and thus increase recycling), that diversion is dependent on subsequent choices by the food waste generator and – if the waste is being sent down the drain – details of the receiving WRRF and decisions by that WRRF. Food waste may still end up in a landfill or incinerator after pre-processing.

For technologies that produce semi-dry or dry outputs (pulpers, dehydrators, aerobic in-vessel units), generators must decide where to send the output, with a landfill or incinerator still an option. Generators may recycle the pre-processed food waste into a stable soil amendment by hauling it off-site for centralized composting or, in the case of dehydrators and aerobic in-vessel units, by further curing it on-site or off-site. Facilities may also send the semi-dry or dry pre-processed food waste to a landfill or incinerator.

For technologies that produce liquid outputs (grinders and biodigesters), generators typically send the output down the drain. Whether biogas is recovered from the food waste is dependent upon whether the receiving WRRF has AD capabilities. After treatment (with or without AD) at a WRRF, biosolids remain. These biosolids may be recycled (with or without further processing) and land applied as a soil amendment – or they may be landfilled (e.g., because the landfill tipping fees are more economically viable for the WRRF than land application or other beneficial use options). Generators may also collect liquid outputs and haul them off-site for biogas recovery via AD at a stand-alone AD or an AD at a WRRF. Biosolids will remain and, as above, may be recycled and land applied, or landfilled.

Whether the use of these pre-processing technologies increases the frequency of recycling is unknown – and is impacted by a combination of commercial decisions (i.e., where they send output) and local infrastructure (i.e., what recycling options are available). For areas where the local WRRF has AD, the ease of sending food waste down the drain after pre-processing (and through the sewer to the WRRF) may encourage recycling. In areas where composting or AD facilities are not conveniently located, technologies like dehydrators and aerobic in-vessel units may offer an opportunity for recycling; but in these same locations, sending food waste down the drain will not result in recycling.

Do pre-processing technologies reduce the environmental impact of food waste?

The net environmental value of commercial food waste pre-processing technologies is not well understood and likely depends upon whether they lead to increased recycling of food waste (i.e., the previous research question). Based upon the information available, the core environmental benefits of pre-processing systems appear to be:

1) *Reduced fuel use and GHG emissions from waste hauling.* If the food waste is to be transported by truck to its next destination, be it a composting or AD facility or a landfill or incinerator, many of these technologies significantly reduce the volume and/or weight of food waste that must be transported, thus reducing associated fuel use and GHG emissions. These technologies also may reduce the frequency of hauling required.

2) *Analytical tools to aid food waste prevention.* Some types of pre-processing technologies, such as biodigesters, come equipped with scales and analytical tools, providing users with useful information about the types and amounts of food wasted, which can support waste prevention. Food waste information and tracking tools, such as those from Leanpath or Winnow, can also be procured without a biodigester (Leanpath, 2021; Winnow, 2021).

3) *Enabling the creation of recycled products.* Dehydrators and aerobic in-vessel units can transform food waste into a useable product on-site, after additional processing and/or curing time, thus directly enabling recycling. Technologies that produce a liquefied output (grinders and biodigesters) also prepare food waste for AD; however, food waste can be hauled off-site for recycling without pre-processing.

However, these benefits must be balanced against known and potential environmental impacts of the use of these technologies, such as:

1) *Energy and water use to operate the pre-processing technology.* Some pre-processing technologies use substantial amounts of energy and water during operation. A comparison of energy use by technologies, and the fuel savings during transportation and energy recovery for pre-processed food waste hauled to AD, for technologies that reduce hauling weight was not available in the literature.

2) *Fugitive methane emissions.* As food waste travels through the sewer system and continues to break down, it may generate methane emissions. A comparison of food waste fugitive emissions from sewer and from landfill was not available in the literature, nor was a comparison of landfill methane emissions from unprocessed and pre-processed food waste.

3) *Energy use for sewer transport and treatment at WRRF.* Where sewer conveyance is assisted by pumping systems, rather than gravity systems, transporting liquefied waste to WRRF increases the system's energy use. Increased energy may also be needed to treat liquefied food waste, which is typically has higher levels of BOD, TSS, and FOG than sewage. Liquefied food waste can also contain nitrates, phosphates, unbeneficial bacteria, and other pathogens that must be treated. Similar concerns may arise for treatment of excess water removed during the pulping process and reconstituted steam removed by the dehydration process.

4) *Increased pollution in direct discharges from combined sewer systems.* Where combined sewer outfall (i.e., one pipe transports rainwater runoff, domestic sewage, and industrial wastewater) exists, increased food waste being discharged into the sewer could increase the organic pollutant load of direct discharge into surface waters after heavy rains.

5) *Reduced focus on the prevention of food waste.* Many pre-processing technologies reduce the costs associated with managing food waste (e.g., hauling costs and landfill tipping fees), thus may lower the financial incentive for reducing the amount of food waste generated. While no literature exists on commercial sector food waste decision-making, research on the residential sector demonstrates decreased concern or guilt about food waste when recycling occurs that may lead to decreased prevention of food waste (McDermott et al., 2019; Neff et al., 2015).

The available literature does not quantify these potential benefits and impacts, thus the balance between them is not yet fully understood. In general, pre-processing technologies that send wastewater down the drain partially or wholly shift the burden of food waste management from landfills to WRRFs and municipal sewage systems. The net environmental burden of this shift has not been thoroughly explored in the literature.

It is also unclear from the available literature how many of these technologies compare to one another as well. The limited data available indicates hauling liquid outputs by truck from the commercial generator to an AD facility may provide greater GHG benefits than sending the food waste down the drain to a WRRF with AD (California State Water Resources Control Board (SWRCB), 2019; Parry, 2012) but other pathways have not yet been compared.

8. CONCLUSIONS AND RESEARCH GAPS

In this issue paper, EPA sought to understand the environmental benefits and impacts of commercial food waste pre-processing technologies, identify any potential unintended environmental consequences, and inform whether (and to what extent) policymakers should encourage the use of each class of pre-processing technology. Because interest in food waste pre-processing, like food waste in general, has grown rapidly in recent years, it is an emerging subject of scientific research. The state of the science and conclusions that can be drawn from the current body of research are presented in Section 8.1. Section 8.2 identifies research gaps that could be help inform policymakers and businesses about the environmental value of these technologies.

8.1. Conclusions

Food waste pre-processing technologies, such as grinders, biodigesters, pulpers, dehydrators, and aerobic in-vessel units, are being employed by commercial food waste generators in the United States to meet economic or environmental goals and/or comply with state and local organic waste laws. Many of these technologies are marketed with strong messaging about their environmental benefits, but little peer-reviewed research has been done to evaluate these claims. While only a limited number of food waste pre-processing technologies are being used in the United States currently, this number may grow due to economic, environmental, or regulatory drivers. Thus, it is important to understand the environmental value of these technologies, both in current use and if they were used at scale (i.e., by many facilities) in a particular geographic area. All the pre-processing technologies discussed in the report require energy and/or water to operate, and this must be considered in any analysis of the environmental value of these technologies.

Currently, grinders and biodigesters appear to be the most popular pre-processing choices of commercial food waste generators (Wright and Jones, 2017), but pre-processing technologies are often used in concert with one another. For example, grinders are often paired with pulpers to remove excess water from the slurry created by the grinder if the intended destination is not a WRRF, or a dehydrator may be paired with a pulper (with or without a grinder) to further remove water (Figure 11).

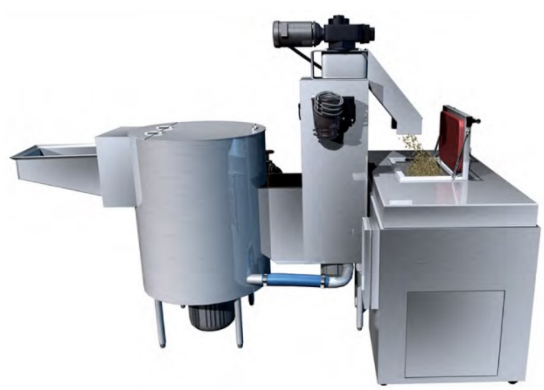


FIGURE 11. PULPER PAIRED WITH A DEHYDRATOR TO MAXIMIZE THE WATER REMOVED FROM FOOD WASTE

Photo Credit: Somat (2012)

Technologies like grinders and biodigesters, which typically discharge liquid effluent into the sewer system,[18] shift the burden of managing food waste from landfills to WRRFs and municipal sewage systems, and the implications of this shift are not well understood. Sending additional organic waste, high in BOD, TSS, and FOG, through the sewer can result in fugitive methane emissions and may require additional energy for pumping systems and water

[18] At least one model offers the ability to collect effluent and haul it by truck to an AD facility.

treatment processes. This waste can also cause operational problems for the water treatment systems, especially in low flow, combined, or aging systems. For example, effluent with high BOD may interact with sulfates from sewage to create hydrogen sulfide, which corrodes pipes, and effluent with FOG may clog pipes resulting in “slugs” that must be removed. There are also regulatory implications, including those under the National Pretreatment Program, for pollutants like FOG that interfere with WRRF operations. If the receiving WRRF has AD capabilities, bioenergy may be created from the energy potential of the food waste. However, not all WRRFs have AD, and the food waste may lose energy potential as it travels through the sewer system and earlier parts of the WRRF. In cities and states with landfill bans for commercial organics, utilizing these on-site systems may help a generator stay under the 1 ton/week threshold, and thus continue to utilize disposal (rather than recycling) for what remains.

Many of the potential environmental impacts of grinders and biodigesters are not quantified in the literature, so they cannot yet be compared to the impacts of landfilling food waste (the most common alternative) or to hauling unprocessed food waste to facilities for AD or composting (recommended over landfilling in EPA’s Food Waste Recovery Hierarchy). Available data indicates greater GHG emissions benefit for trucking effluent from the generator to an AD unit versus sending the same effluent via sewer conveyance to a WRRF with AD for this reason. Also, biodigesters typically include information and tracking tools which can enable the prevention of food waste (the most preferable strategy in EPA’s Food Waste Recovery Hierarchy). The realized benefits of these tools have not yet been reported in the literature.

A shift in financial burden may also occur with the use of pre-processing technologies that send food waste down the drain. Commercial food waste generators that grind and send food waste down the drain avoid paying tipping fees to landfills for this waste, but unless fees are imposed on the generators by the WRRF, municipal ratepayers may bear the added costs of sewer maintenance and additional treatment. In addition, many of the concerns with these technologies could multiply in scale if grinders and/or biodigesters become more broadly adopted among commercial food waste generators. For example, if many more generators within the service area of a municipal WRRF begin to dispose liquified food waste down the drain, the treatment system may not be able to handle the increased load.

Other technologies, such as pulpers, dehydrators and aerobic in-vessel units, produce dry outputs which can be further processed or cured on-site into soil amendments, or sent to composting facilities, landfills, or incinerators. The soil amendments created are not compost in the traditional sense, and much remains to be learned about their stability and suitability for different uses. The dry outputs are lower in weight and volume than unprocessed food waste, so if it is sent off-site, hauling-related fuel use and GHG emissions are reduced. Pulper and dehydrators remove water from the food waste and typically send this water down the drain, which may raise similar concerns to those noted above for grinders and biodigesters.

Based the current state of available research, EPA cannot conclude whether the environmental benefits of pre-processing commercial food waste using these technologies (and sending the waste for further processing at a composting or AD facility, WRRF, landfill, or incinerator) are greater than simply hauling unprocessed waste directly to the intended destination, be it a composting or AD facility, WRRF, landfill, or incinerator. EPA encourages the diversion of food waste streams to composting or AD operations, rather than landfills and incinerators, but cannot yet conclude whether or how the use of pre-processing technologies changes the environmental benefits or impacts of these choices.

A robust body of peer reviewed information is not available that documents and evaluates the overall benefits and impacts to the environment of the pre-processing technologies discussed in this issue paper. In the absence of this information, this issue paper summarized the limited information available in non-peer-reviewed sources, including case studies, interviews, and manufacturer specifications and marketing materials. Given the uncertainties and lack of independent data on these technologies, additional research is needed to better understand the environmental benefits and costs of pre-processing technologies. The limited information that is available should be substantiated through peer-reviewed research or an independent testing organization before drawing actionable conclusions.

8.2. Research Gaps

Based on the information reviewed for this issue paper, additional data collection and original research (independent of equipment manufacturers) on the topics discussed below will increase understanding of the overall environmental benefits and impacts associated with the use of food waste pre-processing technologies. Addressing these research gaps can help decision makers and stakeholders evaluate the available technologies relative to one another and relative to other food waste management options. Better information and more informed decision making has the potential to reduce the overall environmental footprint of food waste in the United States, to increases awareness about the environmental issues associated with food waste management, and to encourage innovation in technology and practices. Priority research needs include:

- **Life cycle assessment of the use of on-site pre-processing technologies in addition to, or in lieu of, traditional food waste pathways.** In-depth LCA studies are needed to determine the net environmental value of using commercial food waste pre-processing technologies. Technologies should be considered individually and in combinations seen in the field (i.e., a grinder, pulper, and dehydrator paired together on-site). In order to perform this life cycle assessment, many of the knowledge gaps listed below must be filled.

- **Impact of pre-processing technologies on generators' choice among food waste pathways.** Data should be collected on the current destination (e.g., down the drain, composting, anaerobic digestion, landfill, or combustion) of pre-processing end products to determine whether they may be enabling or increasing recycling of food waste.

- **Impacts of "wet" pre-processing outputs on municipal sewer systems and WRRFs.** Research is needed to determine whether technologies that send liquefied food waste down the drain (i.e., grinders and biodigesters) and those that send wastewater extracted from food waste down the drain (i.e., pulpers and dehydrators) have adverse effects on the municipal sewer system and WRRFs. Potential concerns include pipe corrosion, clogs, and the impacts of receiving large or inconsistent volumes of additional organic matter with high levels of BOD, TSS, and FOG on WRRFs. In addition, issues of scale should be studied, such as the potential change to the net environmental burden if growing adoption of these technologies leads to more liquified food waste being sent down the drain.

- **Energy potential of pre-processed food waste slurry sent "down the drain."** Research is needed to clarify how the potential for energy or biogas to be created from food waste is impacted when the waste first travels through the sewer system and passes through various levels of wastewater treatment prior to reaching the anaerobic digestion unit at the WRRF. Research is also needed to quantify the impact of biodigester use on energy potential of food waste prior to sewer conveyance.

- **Fugitive methane emissions from sewer conveyance.** Research is needed to quantify fugitive methane emissions from pre-processed food waste as it travels through the sewer.

- **Independently verified operating and performance data.** All the current data on the technologies' processing capacities, volume/weight reduction, and energy and water usage included in this paper are provided by technology manufacturers. Although the information may be accurate, independent, peer-reviewed research is needed for it to be substantiated. In addition, consistent measurement methods and metrics would support better comparisons among technologies. For example, the specifications should be measured per ton of food waste (e.g., gallons of water used per ton of food waste, kWh of energy used per ton of food waste).

- **Land application of dehydrated food waste.** A limited number of case studies on this topic provide mixed and inconclusive findings. In some case studies, the land application of dehydrated food waste results in fungal growth, odor, and vector attraction, like flies. Other case studies have found there are no noticeable issues when the dehydrated food waste is land applied. Outcomes might depend on the type of food waste feedstock, the moisture content, the local climate, curing time, destination (e.g., farm or lawn), or other factors. More specific studies are needed to determine if land applying cured, dehydrated food waste is recommended in certain instances or with certain type of food waste inputs.

- **Contamination introduced by pre-processing technologies.** Food waste streams, including pre-processed food waste, may contain or be associated with undesirable contaminants[19] such as plastic (e.g., from packaging), chemicals of concern, or pathogens. Research is needed to characterize how levels and types of contamination are affected by commercial food waste pre-processing.

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[19] A discussion of plastic and persistent chemical contaminants in food waste streams can be found in two other EPA reports in this series: "Emerging Issues in Food Waste Management: Plastic Contamination" (EPA 600-R-21-001, August 2021) and "Emerging Issues in Food Waste Management: Persistent Chemical Contaminants" (EPA 600-R-21-002, August 2021).

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APPENDIX A. LITERATURE SEARCH METHODOLOGY

This appendix presents the literature search methodology used to identify, screen, and manage literature sources for *From Farm to Kitchen: The Environmental Impacts of U.S. Food Waste* and associated issue papers like this one on pre-processing technologies. The objective of the literature search was to identify the latest scientific information about food waste and food waste reduction, including emerging technologies and approaches for prevention, reuse, and recycling. In addition, analysis of the literature helped to identify knowledge gaps and the most important areas for future scientific research.

Section A.1. Methodology for Peer-Reviewed Literature describes the literature search methodology for peer-reviewed literature sources, and Section A.2 describes the identification of governmental and non-governmental reports that are not published in the peer-reviewed scientific literature, referred to as “gray literature” in this methodology.

This literature search identified and prioritized 3,219 peer-reviewed sources, 1,723 of which were screened as relevant to the scope of the From Farm to Kitchen report and issue papers. These sources, as well as the key gray literature (see Section A.2. Methodology for Gray Literature) and additional key sources identified in supplemental, targeted literature searches, served as the primary corpus of literature from which literature synthesis and report development were performed. The report and associated issue papers were developed by primarily using the literature identified through this methodology but were not limited to this set of literature as additional sources were identified subsequently (e.g., from peer-review recommendations).

A.1. Methodology for Peer-Reviewed Literature

Peer-reviewed literature was identified with a search of selected publication databases using keywords and Boolean logic defined in this section. Titles and abstracts of the publications returned by the literature search were processed to eliminate duplicates and then screened to identify a subset of “key” sources that meet criteria for relevance and usefulness for the report or issue papers. Key sources were “tagged” to pre-defined topics to assist authors in identifying the most relevant sources for particular topics covered in the report.

Peer Reviewed Literature Search Strategy

The search of peer-reviewed literature focused on references relevant to the scope of the food waste report and issue papers from 2010–present, with special priority given to more recent papers, which were considered to be 2017–present. A targeted search to identify review papers from 2014–present was performed. During development of the report and issue papers, additional targeted searches were performed as needed within the 2010–present corpus of literature, and subject matter experts also identified key sources, some of which were dated in 2020 or 2021.

The following databases were searched for relevant peer-reviewed literature:

- **AGRICOLA (AGRICultural OnLine Access):** AGRICOLA records describe publications and resources encompassing all aspects of agriculture and allied disciplines, including animal and veterinary sciences, entomology, plant sciences, forestry, aquaculture and fisheries, farming and farming systems, agricultural economics, extension and education, food and human nutrition, and earth and environmental sciences; Produced by the National Agricultural Library (NAL), U.S. Department of Agriculture.
- **AGRIS:** AGRIS facilitates access to publications, journal articles, monographs, book chapters, and grey literature - including unpublished science and technical reports, theses, dissertations and conference papers in the area of agriculture and related sciences; Maintained by the Food and Agriculture Organization of the United Nations (FAO).
- **EBSCO:** EBSCOhost Research Databases: Academic Search Complete; Energy & Power Source.

- **PubMed:** US National Library of Medicine National Institutes of Health.
- **Web of Science:** Web of Science Core Collection, refined by Research Area. Clarivate Analytics.

Table A-1 outlines the searches performed and the combinations of keyword sets and Boolean operators used to search each database. Four distinct sets of keywords were used to capture references with relevance to food waste, pathways of food waste and food waste reduction, environmental impacts of food waste, and emerging issues in the area of food waste. Sets were combined using Boolean logic to identify relevant references for screening and evaluation. Search results were limited to publications written in English.

For each search, all references were downloaded into EndNote and then DeDuper was used to remove duplicate references (i.e., references that appeared in more than one of the databases searched). DeDuper is a tool that uses a two-phase approach to identify and resolve duplicates: (1) it locates duplicates using automated logic, and (2) it employs machine learning to predict likely duplicates which are then verified manually.

TABLE A-1. SEARCH STRATEGY KEYWORDS

Set	Search Keywords and Boolean Logic
Food Waste	Food AND (waste OR loss OR "FLW") AND (prevention OR system OR consumed OR Surplus OR Excess OR Uneaten OR reduction OR supply OR demand OR Per capita OR Edible OR Inedible OR Safety OR recall OR packaging OR Preventable OR Drivers OR Spoilage OR perishable OR Freshness OR harvest OR transportation OR Processing OR manufacturing OR supermarket OR grocer* OR reuse OR recycling OR seasonal OR projection OR future OR economic)
Pathways	("Source reduction" OR Awareness OR education OR campaign OR LeanPath OR Photodiary OR storage OR Labeling OR (Refrigerator AND temperature) OR Cellar OR Frozen OR "Meal kits" OR packaging OR Donation OR Upcycling OR "Animal feed" OR "Anaerobic digestion" OR Co-digestion OR "Aerobic processes" OR Composting OR "Controlled combustion" OR Incineration OR Landfill OR "Land application" OR de-packaging OR "shelf life")
Environment	Environment* AND (use OR usage OR impacts) AND (climate OR "Air emissions" OR "Water pollution" OR Pesticide OR Land OR Irrigation OR Energy OR fertilizer OR water OR Herbicides))
Emerging Issues	((Compost* or compostable) AND (packaging OR serviceware OR utensil OR tableware OR plate OR bowl))

To efficiently screen results, references were prioritized using topic extraction, also referred to as clustering, with ICF's Document Classification and Topic Extraction Resource (DoCTER) software. The titles and abstracts from all search results (i.e., AGRICOLA, AGRIS, EBSCO, PubMed, and Web of Science) were run through DoCTER's topic extraction function. Each study was assigned to a single cluster based on text similarities in titles and abstracts. Clusters were prioritized or eliminated for screening based on the relevance of the keywords identified. Only prioritized studies published from 2014–present were screened for relevance.

Peer Reviewed Literature Screening and Tagging

The sources identified by the literature search were screened to identify those that are considered "key" sources for the report and issue papers. To be considered a key source, a publication had to be relevant to the project scope and exhibit at least most of the general attributes provided in EPA's Quality Assurance Instructions for Contractors Citing Secondary Data, summarized below:

- Focus: the work not only addresses the area of inquiry under consideration but also contributes to its understanding.
- Verify: the work is consistent with accepted knowledge in the field or, if not, the new or varying information is documented within the work; the work fits within the context of the literature and is intellectually honest and authentic.
- Integrity: Is the work structurally sound? In a piece of research, is the design or research rationale logical and appropriate?
- Rigor: the work is important, meaningful, and non-trivial relative to the field and exhibits enough depth of intellect rather than superficial or simplistic reasoning.
- Utility: the work is useful and professionally relevant; it contributes to the field in terms of the practitioners' understanding or decision-making on the topic.
- Clarity: Is it written clearly and appropriately for the nature of the study?

Relevance to the project scope was evaluated against the specific topics and criteria. In particular, relevant topics included:

- Characterization of U.S. food waste, including but not limited to kinds of food, sources, amounts, and reasons for loss or waste.
- Reduction strategies, including composting, anaerobic digestion, secondary industrial uses, animal feed, donation, and source reduction.
- Lifecycle environmental costs and benefits of choices between and within levels of the EPA food recovery hierarchy.
- Pre-processing technologies (e.g., grinding, heating, digestion) and their environmental implications in use, including their potential to help reduce food waste.
- Food packaging and service ware and their relationships to food waste, including ways packaging may impact prevention and recycling of food waste or use and value of products created by recycling.
- Chemical contaminants (e.g., PFOS, PFAS, persistent herbicides) and the risk and problems posed in food waste streams.
- Food system trends to identify well-recognized trends in the U.S. food system that may impact food waste and summarize what has been written about their potential impacts.
- Unharvested or unutilized crops that do not reach the consumer market.
- Waste or loss during transportation, food processing/manufacturing/packaging facilities, or wholesale food distributors.
- Waste or loss at supermarkets (e.g., unsold or spoiled products), restaurants, and households.
- Existing economic, social, and cultural drivers of food waste or barriers to food waste prevention, reuse, and recycling efforts.

The following topics were not considered relevant:

- Unutilized livestock (e.g., due to market forces, routine mortality) or unharvested or unutilized feed crops.
- Regulatory drivers of food waste or barriers to food waste prevention, reuse, and recycling efforts.

- Broad economic impacts (e.g., on the agricultural sector) of food waste production, prevention, reuse, and recycling efforts; economic costs and benefits for entities resulting from food waste production and reduction strategies (e.g., as drivers).

The litstream™ tool was used to screen for key sources based on reference titles and abstracts. litstream™ facilitates screening by one or two independent reviewers, automatically compares categories, and identifies discrepancies for resolution by another individual. litstream™ also allows users to design flexible data-extraction forms, thus enabling the review team to perform the screening and tagging steps of the systematic review within one software tool.

For publications identified as key sources, full text files were retrieved with EPA's Health & Environmental Research Online (HERO) database as requested by authors. Then, authors used the full text of the key sources to confirm topic area relevance and incorporate them into their literature synthesis.

A screening and tagging guidance document was developed to provide instructions and keywords associated with the tags. To ensure internal consistency and accuracy of the litstream™ screening and tagging, a pilot screening of 5–10 reference (per reviewer) was performed to provide feedback to the screening team. Additionally, 10% of each reviewer's assigned citations were reviewed by a second reviewer. Discrepancies between the primary and secondary reviews were resolved by lead authors.

A.2. Methodology for Gray Literature

Identifying key sources in the "grey literature" was essential to a comprehensive review and synthesis of the report and issue papers. The review methodology for grey literature included a search strategy and approaches for screening and tagging key sources.

Grey Literature Search Strategy

The peer-reviewed literature search was supplemented with relevant grey literature from the sources listed below:

- Grey literature publications cited by key sources identified by the EPA from prior related research. These sources were screened as potential key sources.
- Grey literature publications identified by peer reviewers and subject matter experts who reviewed pre-peer review drafts of the reports and issue papers (see the acknowledgments sections in the report and each issue paper). These sources were considered key sources without screening.
- Targeted google and domain searches for selected governmental or non-governmental organizations.

The titles and URLs of potential sources identified by the searches were compiled in an Excel file used for subsequent screening.

Grey Literature Screening and Tagging

Grey literature was screened in Excel using the key source criteria defined for peer-reviewed literature (see Section A.1. Methodology for Peer-Reviewed Literature Screeners applied the criteria to each of the potential sources in the database file described above (i.e., titles and URLs identified from searches). For each URL, the screeners evaluated the sources by reviewing abstracts, executive summaries, forewords, keyword lists, or tables of contents. When a screener identified a key source, they recorded additional information including publishing organization, author names, and year for the source to proceed to tagging.

Tagging was only performed for the grey literature identified as key sources, and the same tags as used for peer-reviewed literature (see Section A.1. Methodology for Peer-Reviewed Literature) were used for grey literature. screeners applied the tags in columns within Excel.

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