EMERGING ISSUES IN
FOOD WASTE MANAGEMENT

Plastic Contamination

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Executive Summary

Food waste is a major global environmental, social, and economic challenge. Recognizing the critical importance of reducing food loss and waste, in September 2015, the U.S. 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 U.S. EPA's strategies to help meet this goal is to encourage diversion of food waste from landfills to composting and anaerobic digestion facilities to reduce methane emissions and recover value (e.g., nutrients or energy) from the food. However, stakeholders (e.g., municipal governments, waste haulers, compost facility operators) have raised concerns about the presence of plastic in food waste streams. To achieve the environmental benefits of diverting food waste from landfills on a large scale, EPA must better understand the potential risks to human health and the environment of applying plastic-contaminated compost or digestate products to land and the most effective strategies to prevent or mitigate these risks and communicate these findings to affected stakeholders.

- The primary source of plastic contamination in food waste streams collected for processing at compost and anaerobic digestion facilities appears to be food packaging and containers, most likely from residential, commercial, and institutional sources. Food itself is also a source of microplastic particles. The level of plastic contamination present in food waste streams is not well characterized in the scientific literature. A recent analysis found approximately 300,000 pieces of microplastics per kilogram of food waste collected from grocery stores in the United States. In addition, limited data from Washington State and Oregon reports plastic contamination rates up to 2.8 percent (by weight) in mixed waste streams including food waste that were destined for composting or anaerobic digestion. Plastic contamination rates in purely food waste streams may be higher, as available evidence indicates plastic contamination levels in food waste streams may be higher than that of other organics waste streams, such as yard waste.

- Techniques to prevent plastic contamination in food waste streams, such as education and outreach, cart tagging programs, and hauler contract provisions are being used in some jurisdictions. Limited data on prevention programs shows mixed results. If successful, prevention could reduce the complexity and increase the desirability of processing food waste streams. Processing facilities also use a variety of approaches, such as manual picking, screens, and de-packaging technologies, to reduce the amount of plastic contamination in food waste streams before processing. These approaches can be costly and are not fully effective. Plastic material, including microplastic, has been repeatedly observed in finished products. Further, it is unclear to what extent technologies (e.g., shredders, grinders and de-packagers) may inadvertently introduce microplastics or nanoplastics into the end products by breaking down larger pieces of plastics.

- Current tests for physical contaminants are labor intensive and costly, making it impractical to process large sample sizes in the laboratory. Tests commonly used in the United States do not account for contaminants less than 4 mm in size and thus may miss some microplastics (defined as plastic particles <5 millimeters [mm] in size in any one dimension). Also, compost is heterogenous in nature, and physical contamination levels can vary between different samples

- Much remains uncharacterized about the environmental fate of and exposure to plastic particles in composts and digestates generated from food waste and used as soil amendments, making it challenging to evaluate risks to human health and the environment. The available literature does not provide substantial evidence of environmental or human health effects that are occurring as a result of plastic contamination in finished compost and digestate products produced using food waste streams. It is also unclear how the risks associated with these products generated from food waste would compare to those of background levels of plastic contamination and other sources of plastic contamination in the environment, such as other soil amendments (synthetic or made from wastewater sludge and biosolids).

- Owing in part to the uncertainty about environmental exposures and risks, regulations and standards implemented to reduce the amount of plastic present in composts and digestates generated from food waste and used as soil amendments vary by location. In the United States the federal government does not regulate plastic contamination in finished products applied to land; however, some U.S. states and international governments do. These limits vary in both the allowable levels of contamination and fragment size thresholds. European standards generally address smaller fragment size thresholds than U.S. state regulations. Overall, the regulations in the United States typically do not address plastic fragments less than 4 mm, and regulations identified for other countries do not address sizes smaller than 1 mm. Limits may be set based upon detection levels, which vary along with the cost and level of complexity of available testing methods, and aesthetic concerns (e.g., preventing visible plastics) given that exposure and risk analysis is not available.

- Regardless of risks to human health and the environment, the presence of visible plastic particles in finished products reduces their value and marketability. Processing facilities sometimes prohibit food waste streams or reject incoming food waste streams collected for processing at compost and anaerobic digestion facilities due to plastic contamination levels, thus reducing the amount of food waste diverted from landfills.

- Plastic contamination may reduce the environmental and economic benefits of composting and anaerobic digestion of food waste. For example, an initial study indicated plastic contamination may impede the production of methane from food waste during anaerobic digestion, and another study found the presence of microplastics can alter greenhouse gas and ammonia emission levels during composting.

- Compostable plastics present a unique set of operational challenges to both consumers and facilities seeking to compost these products when mixed with food waste. Compostable plastic materials can look similar to those made with conventional plastics, leading to contamination of the compostable food waste stream with conventional plastics, and to the removal of the compostable plastics along with conventional plastics during screening and de-packaging at processing facilities, eliminating the potential environmental benefit of compostable materials.

Plastic contamination in food waste streams and its implications for food waste management, and for human health and the environment, is an emerging issue in the early stages of investigation. Scientifically rigorous data are needed to address several important research gaps:

- Research to discover the level of plastic contamination and associated particle sizes (e.g., microplastics or nanoplastics) in finished composts and digestates generated from food waste and used as soil amendments in the United States.

- Research to ascertain the contribution of food waste to plastic contamination in compost and digestate used as soil amendments.

- Research to determine the impacts of technologies (e.g., shredders, grinders and de-packagers) commonly used by processors on the level of plastic contamination and size of plastic particles.

- Research to determine the effect of microplastic contamination on greenhouse gas and ammonia emissions levels during composting and methane yield from anaerobic digestion.

- Research to identify the most effective strategies to prevent plastic contamination in food waste streams.

- Research to assess exposure and the potential risks to human health and the environment from land application of plastic-contaminated compost and digestates.

Plastic contamination in food waste presents challenges for a broad range of stakeholders, including but not limited to those involved in waste management and processing facilities, and those who purchase and intend to use compost and digestate as soil amendments. Many key players contribute to the plastic contamination found in food waste streams, including packaging and food serviceware manufacturers, food processors, consumers, businesses, and institutions, and all of them can be a part of the solution.

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1. INTRODUCTION

The purpose of this issue paper is to inform federal, state, and local policymakers of the latest science related to plastic contamination in food waste streams and its impacts on food waste recycling, the environment, and human health, and to prioritize research needs in this area.

1.1. Background

Wasted food is a major global environmental, social, and economic challenge. When food is produced but unnecessarily wasted, also wasted are all the embedded resources required for the food to be grown and make its way through the food supply chain to consumers. In addition, food waste is typically landfilled in the U.S., resulting in significant methane emissions. The U.S. Environmental Protection Agency (EPA) estimates that more food reaches landfills than any other single material in our everyday trash, constituting 24 percent of landfilled municipal solid waste (MSW) (U.S. EPA, 2020a). Reducing food waste will help the United States address climate change, as approximately 20 percent of total U.S. methane emissions come from landfills (U.S. EPA, 2020d).

Recognizing the critical importance of reducing food loss and waste, in September 2015, the EPA and U.S. Department of Agriculture (USDA) announced the *U.S. Food Loss and Waste Reduction Goal* to halve food loss and waste by 2030[1] (U.S. EPA, 2020f). One of EPA's strategies to help meet this goal is to encourage diversion of food waste from landfills to composting and anaerobic digestion facilities to reduce methane emissions and recover value (e.g., nutrients or energy) from the food. EPA estimates that in 2018 only 4 percent of wasted food in the United States was composted and 8 percent was anaerobically digested, while much of the remainder was sent to landfills (56 percent) or combusted (12 percent) (U.S. EPA, 2020a, f). Many states and municipalities have also established food waste reduction goals or initiated programs to reduce food waste. For example, laws and executive orders in at least three states (New Jersey, Oregon, and Washington) have established goals to reduce food waste by half by 2030 (NCSL, 2020; State of Oregon, 2020; State of New Jersey, 2017), and six states (California, Connecticut, Massachusetts, New York, Rhode Island, and Vermont) have enacted organic waste recycling laws to divert food waste from landfills.

Given these developments, interest in alternatives to landfilling or incinerating food waste, such as composting and anaerobic digestion, has increased. However, stakeholders (e.g., municipal governments, waste haulers, compost facility operators) have raised concerns about the presence of plastic in food waste streams.

Plastic contamination found in food waste streams can include fragments and films of varying size that originate from material such as food packaging, containers, bags, produce stickers, and serviceware (Harrington, 2015). Plastic contamination in food waste causes operational problems for compost and anaerobic digestion facilities and can reduce the value of their final products (U.S. EPA, 2019a; Arsova, 2010). Facilities sometimes prohibit food waste streams or reject contaminated food waste streams for this reason, thus reducing the amount of food waste diverted from landfills. Plastic-contaminated compost and digestate products may also pose risks to human health and the environment when applied to land; however, data is very limited.

As EPA seeks to increase the amount of food waste composted or anaerobically digested rather than landfilled or combusted, we seek to better understand the nature and magnitude of this problem and find solutions, where necessary.

[1] The goal is to reduce per capita retail and consumer waste by 50% from 2010 levels by 2030.

1.2. Overview

This issue paper reviews and summarizes information available in the literature on:

1) Sources and levels of plastic contamination in food waste streams;
2) Impacts of plastic contamination on the recycling of food waste and use of compost and digestate;
3) Potential risks to the environment and human health caused by land application of plastic-contaminated compost or digestate;
4) Approaches for preventing and mitigating plastic contamination in food waste intended for recycling (including the use of regulatory measures); and
5) Effects of compostable food service products on plastic contamination in food waste streams.

After synthesizing findings in the available literature in each of the five research areas listed above, conclusions and research gaps are presented to guide future efforts.

1.3. Scope and Methods

This issue paper focuses upon plastic contamination in U.S. food waste streams. In the paper, we use the term food waste[2] to describe food that was not used for its intended purpose (i.e., being eaten by people) and is managed in various ways, including composting or anaerobic digestion, or by sending it to landfills or combustion facilities.

The paper includes data from the peer-reviewed literature as well as from publicly available gray literature from government agencies, multi-stakeholder working groups, nonprofit organizations, and industry stakeholders and associations. The sources of this additional information are clearly identified and can provide insights in areas where the peer-reviewed data was sparse. For example, a report from the Washington State Organics Contamination Workgroup (comprising state, county, and city officials plus businesses) provided the most robust information on sources and levels of plastic contamination in food waste streams as well as strategies to reduce plastic contamination in food waste diverted to composting and anaerobic digestion. The search strategy used to identify available peer-reviewed and gray literature is summarized in Appendix A.

Throughout this issue paper, significant findings and conclusions are indicated by sidebars on the left margin of the page.

[2] The term food waste in this report includes everything EPA typically includes in the term "wasted food," except food which is donated to feed people (U.S. EPA, 2020a).

2. PLASTIC CONTAMINATION IN FOOD WASTE

Sources and levels of plastic contamination in food waste streams are discussed in Sections 2.1 and 2.2, respectively.

2.1. Sources of Plastic Contamination in Food Waste Streams

Conventional fossil fuel-based plastics are used in a variety of ways in the food industry, but their primary use is to protect or preserve foodstuffs, thereby helping to reduce the amount of food wasted due to damage or spoilage (Heller, 2019; Wohner et al., 2019; OECD, 2018). Plastic is also used for food product labeling and advertising materials. Despite their role in reducing food waste, some non-compostable plastic does enter the food waste stream, complicating the processing of food waste. (Note: See Section 8 of this paper for a separate discussion of compostable materials.)

The available literature indicates that the primary sources of plastic contamination in food waste streams are food packaging and containers, and more specifically those manufactured as multilayer paper products coated in plastic, which are designed to provide a high level of resistance to water and gas transfer to the food they are meant to protect (Brinton et al., 2018; Barlow and Morgan, 2013).

Examples of these products include frozen-food and take-out containers, cartons for beverages such as juice and milk, plastic-lined paper bags, and paper plates designed to provide moisture protection (Brinton et al., 2018). Other food serviceware, such as plates, serving trays, hot and cold beverage cups, and utensils, are also often collected with food waste, and these can be made of plastic-coated paper (i.e., multilayer paper products) or plastic alone (Cadwallader, 2019).

Other common sources of plastic in food waste streams include non-compostable bags and stickers (Harrington, 2015). Non-compostable plastic bags, including produce bags and can liners, are used to preserve and store food intended for consumption but can enter food waste streams (Oregon Metro, 2020; State of Washington, 2017). While some collection programs allow food waste to be collected in compostable film liners, residents and businesses sometimes use liners made from conventional plastic instead, thus contaminating the food waste stream (Oregon Metro, 2020). Stickers found on produce and other foodstuffs include a layer made of either plastic or vinyl and can be found on many fruits and vegetables to display brand information or price-look up codes (Nosowitz, 2018). Plastic stickers typically are removed before eating fruits and vegetables that have an edible skin or outer layer. However, for fruits and vegetables with skin or an outer layer that is not consumed (e.g., avocado, orange)—or fruits and vegetables that are not consumed at all—the plastic sticker sometimes remains attached to the food material (Nosowitz, 2018) and is collected with food waste streams.

Plastic particles may also enter the food waste stream due to their presence in the food itself. Table 1 presents the range of plastic contamination rates in food as reported in the available literature. Several studies have documented the presence of microplastic particles (MPs) (defined as plastic particles <5 millimeters [mm] in size in any one dimension) in marine organisms that people consume, especially shellfish, and microplastic has also been found in bottled water, table salt, beer, milk, teabags, honey, sugar, and fresh fruits and vegetables (Conti et al., 2020; Kwon et al., 2020; Toussaint et al., 2019).

TABLE 1. PLASTIC CONTAMINATION RATES IN FOOD

Food Item	Number of Plastic Particles[a,b]	Particle Size Category[a,c]	Sampling Location	Reference
United States				
Seafood	0.16–3.84 MPs/g	Microplastic	United States	Keisling et al. (2020), Baechler et al. (2019), Waite et al. (2018), Zhao et al. (2018), Rochman et al. (2015)
Sea salt	0.212 APs/g[d,e]	Conventional plastic	United States	Kosuth et al. (2018)[f]
Beer	0.05 APs/L[e]	Conventional plastic	United States	Kosuth et al. (2018)
Tap water	9.24 APs/L[f]	Microplastic	United States	Kosuth et al. (2018)
Bottled water	325 MPs/L[g]	Microplastic	United States and other countries[h]	Mason et al. (2018)
Outside United States				
Salt	0.11 MPs/g	Microplastic	Multiple countries	Cox et al. (2019)
Sugar	0.44 MPs/g	Microplastic	Germany	Cox et al. (2019)
Seafood	1.48 MPs/g	Microplastic	Multiple countries	Cox et al. (2019)
Honey	0.10 MPs/g	Microplastic	Multiple countries	Cox et al. (2019)
Beer	32.27 MPs/L	Microplastic	Canada, Germany	Cox et al. (2019)
Bottled water	94.37 MPs/L	Microplastic	Multiple countries	Cox et al. (2019)

MPs = microplastics; APs = anthropogenic particles; g = gram; L = liter
[a] Microplastic particles are plastic particles <5 millimeters in size in any one dimension.
[b] Anthropogenic particles are a broad category of particles produced directly or indirectly by human activities, thus showing an anthropogenic origin.
[c] Conventional plastic is a broad category of particles >5 millimeters in size.
[d] Concentration reported in APs/kg; converted to APs/g.
[e] Particles of size >11 µm.
[f] Particles of size >2.5 µm. Kosuth et al. (2018) reported their results as “anthropogenic debris” rather than microplastic because spectroscopic analyses were not performed to confirm their assumption that the particles found were most likely microplastic.
[g] Particles of size >6.5 µm. Note this particle size is greater than the size typically categorized as “microparticles.”
[h] Data from United States and international bottled water combined.

In addition to the different types of plastic products found in food waste streams, the use of many different types of plastic to make these products adds another layer of complexity to the processing of plastic-contaminated food waste streams (WPO, 2008). Specific types of plastic used in the food industry include polyethylene terephthalate (PET), commonly used in soft drink and water bottles; high-density polyethylene (HDPE), commonly used in milk and water jugs; low-density polyethylene (LDPE), commonly used in film products (including bags and sacks) and plastic-coated paper products; and polyvinyl chloride (PVC), polystyrene, polypropylene, and other resins, commonly used to manufacture clamshell containers, trays, caps, lids, egg cartons, loose fill, produce baskets, coatings, and closures (U.S. EPA, 2020c, 2019b; Brinton et al., 2018). The multilayer paper products coated in plastic (discussed above) often use polyethylene, which includes both LDPE and HDPE (WRAP, 2017).

Information on the amounts or percentages of the plastic contamination in food waste streams attributable to each type of product or type of plastic has not been published to date. The overall use of plastic for food packaging and the employment of more sophisticated food packaging technology continues to increase over time (U.S. EPA, 2020b), but the impact on contamination levels is unknown.

2.2. Levels of Plastic Contamination in Food Waste Streams

Comprehensive national studies of plastic contamination levels in food waste streams across the country are not available, but organizations in Washington State and Oregon have collected relevant data. The available data confirms the presence of plastic in food waste streams at the time of collection before it enters composting or anaerobic digestion facilities.

However, because food waste is often collected with other organic waste, it can be difficult to determine how much plastic contamination is attributable to food waste and how much is entering via other organic waste streams, such as yard waste. In addition, often only total contaminant loads are measured, which may include glass and other non-compostable items in addition to plastics (King County Solid Waste Division, 2019a, b; State of Washington, 2017). While weight is the most common metric for contamination, volume measurements can also offer insights, especially given the lighter weight of film plastics compared to other common contaminants such as glass.

In 2019, Oregon Metro completed a Commercial Food Scraps Composition Study to evaluate the amounts and types of contaminants placed in food scrap bins by businesses and their employees in the Metro region that encompasses Portland and 23 surrounding cities (Oregon Metro, 2020). This program is just for food waste destined for composting and anaerobic digestion facilities, and the only acceptable materials are food and compostable film can liners. The study showed that average total contamination in the commercial food scraps stream was 3 percent by weight and 6 percent by volume. Plastic food serviceware made up 1 percent by weight and volume of the samples analyzed. Plastic bags and films made up 1 percent by volume of the samples analyzed. Other contaminants found included yard debris and plants, paper napkins and towels, and fiber-based serviceware. At the time of the study, the program was voluntary. The report notes that contamination may increase when the program changes from voluntary to mandatory in March 2021 (Oregon Metro, 2020).

A report by the King County Solid Waste Division (2019a), including the organics waste stream data for King County, Seattle, and Snohomish County in Washington, reported total contamination levels of approximately 3.9 percent by weight (19,900 tons) of the material collected for processing at compost facilities. This estimate includes plastics and plastic-coated papers, but also other contaminants such as glass. More detailed data from specific jurisdictions can be found in Table 2 and are summarized below. All estimates of composition are by weight.

In King County (excluding Seattle), plastic contamination was 2.8 percent of the materials collected from commercial curbside carts (from businesses and institutions) in March of 2019. No yard waste was collected during that time period from commercial carts, so food waste made up most of the materials along with compostable packaging and paper products (King County Solid Waste Division, 2019a). Also in King County (excluding Seattle), contamination (non-compostable material) made up about 5 percent by weight of the material collected in single-family curbside organics service carts in 2017. This collection was primarily of yard waste (85 percent), with food waste constituting only 6 percent (King County Solid Waste Division, 2018). Recyclable plastic was 0.1 percent of the of material collected, and “other materials” constituted 4 percent. Other materials included animal waste, kitty litter, treated wood, construction materials, Styrofoam, and plastic trash bags (King County Solid Waste Division, 2018).

The City of Seattle’s 2016 Organics Stream Composition Study found that non-compostable contaminants accounted for almost 3 percent by weight of the material collected. In this study, food waste made up approximately 41 percent of the total organic materials collected that were intended for composting, whereas yard waste contributed approximately 46 percent (Seattle Public Utilities, 2018). Estimates were reported separately for certain plastic contaminants as percent of total material collected: non-compostable plastic film (0.7 percent), non-compostable plastic containers (0.2), other plastic (0.1 percent), and polycoated paper (0.3 percent).

The City of Seattle's results were reported individually for the three waste-generating sectors: single-family residential, multifamily residential, and commercial (i.e., business and institutions), though comparisons remain difficult, as the percentage of food waste in each sector's waste stream varied. The percentage of plastic contamination was highest in the organic waste collected from the multifamily residential sector for which food waste constituted approximately 59 percent of the organics collected (the sum of plastic contaminants was 2.2 percent and 0.3 percent was polycoated paper). In the commercial sector, in which food waste contributed roughly 75 percent of the organics collected, the sum of plastic contaminants was 1.9 percent and polycoated paper made up 0.5 percent. In the single-family residential sector, in which food waste contributed only 13 percent of the organics collected, the sum of plastic contaminants was only 0.2 percent and polycoated paper made up 0.1 percent (Seattle Public Utilities, 2018).

TABLE 2. CONTAMINATION RATES IN FOOD WASTE STREAMS COLLECTED FOR COMPOSTING AND ANAEROBIC DIGESTION IN THE UNITED STATES

Area	Feedstock composition	Sector	Contamination Rates in Food Waste Streams	
			Total contamination (by weight)	Plastic contamination (by weight)
King County, WA (excluding Seattle)	6% FW	Single Family Residential	5%	0.1% recyclable plastics
Seattle, WA	13% FW	Single Family Residential	–	0.2%
Seattle, WA	75% FW	Commercial	–	1.9%
Portland, OR and 23 surrounding cities	100% FW and compostable liners[a]	Commercial	3%	2%
Seattle, WA	59% FW	Multi-Family Residential	–	2.2%
King County, WA (excluding Seattle)	100% FW and compostable paper/packaging	Commercial	–	2.8%

Source: King County Solid Waste Division (2019a); Oregon Metro (2020)
FW=food waste
[a] Includes bags for compost collection bins

In summary, the limited available data from Oregon and Washington reports plastic contamination rates up to 2.8 percent (by weight) in waste streams including food waste and destined for composting or anaerobic digestion. Total contamination rates of the same streams are up to 5 percent (by weight). However, plastic contamination rates in purely food waste streams may be underestimated here, as food waste was not the major component of many of the waste streams analyzed. Available evidence indicates plastic contamination levels in food waste streams may be higher than that of other organics waste streams, such as yard waste.

When food scraps were added to curbside yard waste collection programs over the past decade, composting facilities observed an increase in the types and amounts of physical contaminants mixed with the incoming loads of organic waste (State of Washington, 2017). In addition, a report by CalRecycle (2019) indicates that food scraps have a higher percentage of plastic and glass than other feedstocks. Additional data on waste streams primarily composed of food waste would be helpful to confirm magnitude of contamination.

In addition to the visible plastic items that were analyzed in the available waste stream studies, food waste collected for processing is likely to contain microplastic particles of varying sizes (that may or may not be visible). These particles could originate from fragmentation of larger plastic pieces or from the food itself. Preliminary analysis by Golwala et al. (2021) found approximately 300,000 pieces of microplastics per kg of food waste collected from grocery stores in the United States (unpublished data).

The significance of plastic contamination may also be underestimated by measuring contamination by weight, as the smallest particles may pose the greatest risk to human health and the environment. Measuring by volume places more emphasis on the lighter weight plastics, such as film plastics, but neither measurement technique accounts for the potential importance of tiny fragments.

2.3. Sector Contributions to Plastic Contamination

While no comprehensive data exists on plastic contamination contributions by sector, inferences may be drawn about the potential significance of each sector's contribution based upon how food waste is generated and collected in the sector. While food waste is generated all along the supply chain, much of the upstream waste (e.g., on-farm and food processing) is unlikely to be packaged in plastic. For example, many of the drivers of food waste generated during food manufacturing—such as trimming for end-use, processing inefficiencies, equipment malfunctions, human error, and food safety and quality concerns—produce food waste before the products are packaged (CEC, 2019; FAO, 2019; Snyder and Worobo, 2018; ReFED, 2016). Some manufacturing-generated food waste could include plastic packaging, however; consequently, this step in the process remains a potential source of plastic contamination.

Food waste generated from residential, commercial, and institutional sources is likely to include a greater amount of plastic contamination than food waste generated on-farm or from food manufacturing, during which the waste is largely generated before food is put into packages.

For instance, a large share of the food waste stream generated by the commercial sector is packaged food products that are spoiled, expired, mislabeled, or otherwise unfit for consumption (Gorrie, 2015). At residences, commercial locations, and institutions, individuals consume food and then discard uneaten food and any plastic packaging or serviceware into available collection bins, including those designated for composting, recycling, or processing outside of a landfill which results in some mixing of food waste and plastic materials at these locations (State of Washington, 2017).

3. IMPACTS ON FOOD WASTE RECYCLING

The presence of plastic in food waste collected for processing presents operational challenges for composting and anaerobic digestion facilities, making it difficult for them to accept feedstock with high levels of plastic contamination (U.S. EPA, 2019a; State of Washington, 2017; Arsova, 2010). These facilities use a variety of approaches to remove plastic from contaminated feedstock they receive. Despite these efforts, some plastic has been observed in finished materials, including compost (Braun et al., 2020; NSW EPA, 2019; Brinton et al., 2018; Weithmann et al., 2018; State of Washington, 2017). Also, if plastic is not removed from contaminated feedstock before composting or anaerobic digestion, products generated by these facilities will be lower in quality, thereby decreasing their value and ability to be used (see Section 4 for further discussion).

This section describes composting or anaerobic digestion processes, the rejection of contaminated food waste by processing facilities, operational issues caused by plastic contamination in food waste streams, and methods and technologies to remove plastic contamination from food waste. Measures to prevent plastic contamination before it reaches composting and anaerobic digestion facilities are discussed in Section 7.

3.1. Composting and Anaerobic Digestion

The collection and processing of food waste is an important strategy for minimizing environmental and waste management issues related to its disposal (Dilkes-Hoffman et al., 2018). Food waste diverted from landfills can be used to generate energy and recover nutrients. Furthermore, diverting food waste helps to reduce solid waste volumes and greenhouse gas emissions from landfills (Morelli et al., 2020).

Composting, a form of aerobic food processing, involves the decomposition of wasted food in the presence of oxygen. Composting converts organic biological matter into humic substances through decomposition. Decomposition of food waste takes place in aerobically controlled conditions. Factors that affect compost development and influence the stage or direction of the process primarily include the particle size, moisture content, temperature, airflow, and microbes present (U.S. EPA, 2016). Aerobic composting methods include pile composting, aerated static pile (ASP) composting, closed mechanical reactor composting (in-vessel composting), vermicomposting, and less commonly, insect composting (e.g., black soldier fly). Pile composting, also called aerated or turned windrow composting, is the most common composting method; as its name implies, this method includes the creation of piles, typically in long rows, which are mechanically turned to maintain a consistent temperature throughout the pile, for aeration, and to distribute moisture. In ASP composting, organic waste is mixed in a large pile. Layers of loosely piled bulking agents (e.g., wood chips, newspaper) are added to aerate the pile. Piles can also be placed over pipes that deliver air to the pile or draw air out of the pile. In-vessel composting involves feeding organic material into a drum, silo, concrete-lined trench, or similar vessel, which allows for careful control of environmental conditions such as temperature, moisture, and airflow (U.S. EPA, 2016). Pile, ASP, and in-vessel composting have three stages: mesophilic (25°C–40°C), thermophilic (40°C–65°C), and cooling and maturation (10°C–40°C). Finished compost is applied to land to improve soil health, among other benefits.

Anaerobic digestion is the process by which organic material is broken down in an oxygen-free environment to produce renewable energy (e.g., biogas and biofuel) and digestate (e.g., soil amendments). Commercial anaerobic digestion facilities were first introduced in the 1950s (Pham et al., 2015); however, in recent years interest in the technology as a food waste management mechanism has accelerated (Anukam et al., 2019). Some advantages of anaerobic digestion are its limited environmental footprint, high energy recovery potential, and that the resulting digestate can be used in the production of agricultural fertilizer and soil amendments (Braguglia et al., 2018). As of 2016, according to EPA, 198 operational anaerobic digestion facilities process food waste either as stand-alone or co-digestion facilities (U.S. EPA, 2021b).[3] Currently, anaerobic digesters can be found either as stand-alone facilities, on-farm food digesters, or co-digestion facilities located at water resource recovery facilities (WRRFs). Co-digestion means the simultaneous combination of multiple feedstocks (i.e., sewage sludge and food waste) in the digestion system. Anaerobic digestion technologies are widespread, with approximately 40 different

[3] Stand-alone digesters: 68; on-farm co-digesters: 59; co-digestion systems at water resource recovery facilities: 77.

technologies on the market as of 2010 (Arsova, 2010). Digesters are generally one of two styles: wet digesters or dry digesters. Wet digesters are the more common type and process the substrate (e.g., food waste) into a liquid slurry form. Dry digesters treat the substrate in dry form and process it into a stacked pile (Arsova, 2010). The resulting product of anaerobic digestion (digestate) may be dewatered and land applied as a soil amendment, further processed through composting, or landfilled. After additional pressing and/or centrifugation, the liquid fraction (or liquor) of the digestate generated by the dewatering process may be land applied as a liquid fertilizer. The liquor must be fine-filtered prior to application to prevent blockage of feeder pipes or irrigation systems (David et al., 2016).

3.2. Rejection of Contaminated Waste Streams

When food waste arrives at a composting or anaerobic digestion facility, the material is inspected against criteria that have been agreed upon with the waste hauler and the facility (Harrington, 2015). Contracts between waste haulers and facilities may include provisions for the facility to flag a contaminated load, accept a contaminated load at a higher price to offset contaminant-removal costs, or reject a load if the amount of contamination is too high (State of Washington, 2017; Harrington, 2015). Reports indicate that rejected loads may be sent to landfills or combustion facilities instead of being composted or digested (Aspray et al., 2019; ADBA and REA, 2018; Dilkes-Hoffman et al., 2018; OECD, 2018).

The amount of plastic or other physical contaminants present in food waste that warrants rejection by facilities before processing is not reported in the available literature, nor is the frequency with which incoming material is rejected by food waste processing facilities in the United States. However, a 2017 survey of Scottish composters reported that five of the 15 surveyed site operators rejected between one and three loads because of contamination and one site operator rejected eight loads due to contamination (Aspray et al., 2019). Nine of the surveyed site operators did not reject any loads (Aspray et al., 2019). Contamination was defined as plastic, glass, and metal and the amount of plastic present in these rejected loads was not reported.

In addition to rejecting individual loads of food waste, composters may choose not to accept any food waste streams for composting due to concern about plastic contamination levels. A 2019 CalRecycle-funded survey found that 38 percent of large composting facilities in California avoid acceptance of food waste to avoid contamination (CalRecycle, 2019).

3.3. Operational Challenges Caused by Plastic Contamination

Rejection of incoming food waste with levels of plastic contamination above a facility's handling capabilities is critical to maintaining the facility's operations (ADBA and REA, 2018). Inclusion of plastic-containing products in collected food waste streams can create problems for composting and anaerobic digestion facilities, which might not be designed to process feedstock with high volumes of plastic (ADBA and REA, 2018; Brinton et al., 2018).

The overall environmental effect of microplastic contamination in composting operations is still unknown. Under experimental conditions, polyurethane plastics have been observed degrading during composting, and new research indicates microplastics may increase or decrease greenhouse gas and ammonia emissions during composting, depending on the types and characteristics of the plastics (Sun et al., 2020).

It is unknown how composting affects the concentration of microplastics in feedstocks. Given that there is not sufficient data on microplastic contamination of incoming feedstock and outgoing finished products, it is impossible to determine the effect of composting on microplastic concentrations. An experimental study by Chen et al. (2019) indicated that composting decreased microplastics in sewage sludge by almost 44 percent. Additional data needs to be gathered to determine the effect of composting on microplastics in food waste.

In anaerobic digestion, wet digesters and dry digesters typically can accept different levels of feedstock contamination due to the different level of solids in the feedstocks they process (McKiernan, 2015). Wet digesters typically process feedstock with less than 15 percent total solids, whereas dry digesters generally process feedstock with greater solid content (U.S. EPA, 2021b), thus allowing dry digesters to handle more contamination.

Dry digesters typically receive food waste from larger operations, such as grocery stores, which regularly dispose of expired foods or rejected produce (McKiernan, 2015). The different nature and higher content of total solids in the feedstocks sent to dry digesters require a different approach to pretreatment than is used with wet digesters (Garaffa and Gröll, 2013).

In summary, dry anaerobic digesters can handle more contamination than wet anaerobic digesters; however, dry digesters are far less common than wet digesters in the United States. A survey of anaerobic digestion facilities (U.S. EPA, 2021a, b) reported that all digesters located on-farm or at WRRFs employ wet operations, as did 89 percent of the stand-alone digesters in the U.S.

Plastic contamination may also reduce the environmental and economic benefits of anaerobic digestion, beyond reducing the quality of products for land application. In general, anaerobic digestion operators prefer organic waste with a higher dry solids content, like bakery waste, potatoes, meat, and fish, instead of wetter products, like fruit and vegetables, because they yield more biogas after digestion (Sullivan, 2012). However, these drier products tend to be packaged and may arrive as feedstock with greater rates of plastic contamination.

Plastic contamination may also impede the production of methane through anaerobic digestion. An experimental study found that production of methane from the anaerobic digestion of food waste was inhibited in the presence of plastic materials, including polystyrene, polypropylene, and HDPE (Lim et al., 2018). Methane yields were reduced up to 10 percent compared with food waste without plastic contamination and greater reductions were seen when the surface area of the disposable plastic materials was higher (Lim et al., 2018). Under experimental conditions, the authors hypothesized that the reduction could be due to the production of toxic plastic by-products or due to reduced contact between microbes and the food waste (Lim et al., 2018). A study of anaerobic digestion of plastic-contaminated sewage sludge yielded consistent results, with PVC able to decrease methane generation during anaerobic digestion (Wei et al., 2019).

3.4. Removal of Plastic Contamination

Composting and anaerobic digestion facilities employ a variety of techniques to remove plastic and other physical contamination from food waste feedstock. The techniques used to address physical contamination vary among facilities as the quality of incoming material, technical capabilities, and requirements for finished products also differ among these facilities. The methods and technologies are expensive and their effectiveness at removing contamination vary widely (State of Washington, 2017). Compost facility operators surveyed in Washington reported that the most difficult to remove physical contaminants are glass, rigid plastics, small stickers, plastic film (including produce and shopping bags), and plastic garbage bags, and cited safety concerns, costs, and technology limitations as the key challenges to removing these contaminants (State of Washington, 2017).

The primary techniques for separating physical contaminants from incoming food waste are manual and mechanical removal. Facilities use differing technologies to implement these techniques (U.S. EPA, 2021b; State of Washington, 2017; Arsova, 2010). Some facilities employ removal techniques both before (pre-) and after (post-) processing food waste into compost or digestate (Aspray et al., 2019).

Manual Picking

Manual picking or pick lines are commonly used to remove plastic contamination at composting and anaerobic digestion facilities prior to processing, and in some cases again post-processing, similar to manual sorting lines used at materials recovery facilities that are part of recycling programs (Aspray et al., 2019). Typically, the feedstock load is dumped on a large open space or along a moving conveyor system and workers manually separate large, easily identifiable plastic items. Manual picking also affords for removal of other easily identifiable non-plastic contaminants, such as wood, cans, and bottles (State of Washington, 2017).

While manual source separation of packaging is possible, it is difficult, labor-intensive work and may not consistently provide feedstock quality acceptable to anaerobic digestion and composting facilities (Coker, 2019). Beyond manual picking, facilities use a variety of mechanical removal processes, the most common of which include screens, separators, and de-packagers (U.S. EPA, 2021b; State of Washington, 2017). The machines used by compost and anaerobic digestion facilities to mechanically remove contaminants are generally not specific to food waste and are also used in other MSW and materials recovery facilities. Mechanical removal processes vary across facilities and different types of facilities accept different levels of contamination depending on local regulations and individual facility specifications.

Screening Machines

Screening machines, including wind sifters[4], trommel screens[5], and star screens[6], are used to sort out the contaminants through rotation and tumbling of the organic materials over screens. The size of the holes and their ability to capture and remove different sizes of plastic fragments vary (Arsova, 2010). Pre-processing screens have openings of four inches (100 mm) or more, whereas screens used for post-processing or final screening of compost typically have openings one-quarter inch (6 mm) or three-eighths inch (9 mm) wide (Brinton et al., 2018; State of Washington, 2017; BioCycle, 2005). However, screens are available with openings as small as one-eighth inch (3 mm) (Ehm, 2011). Wind sifters are used as a post-processing approach to remove light fractions (including plastics) from screened compost (Aspray et al., 2019).

Separators

Separators add either water or air to the organic waste and use buoyancy and shear force to separate both the light floating materials and the heavy nonbiodegradable materials from the organic material (Arsova, 2010). After pretreatment screening, some wet digestion systems send the waste slurry into hydropulpers in which natural buoyancy and sedimentation help to separate the waste mixture into fractions. Plastics are separated into the light fraction and are skimmed off the top. From there, the waste moves into the grit removal system in which small pieces of heavy material, glass, and sand are removed (BTA International, 2020; Arsova, 2010). In addition to mechanical removal technologies used during pretreatment, some composting facilities use vacuum systems for the removal of plastic films from the final compost (Levis et al., 2010).

De-packagers

De-packagers mechanically separate packaging from recovered food waste and are primarily used during pre-processing (Aspray et al., 2019). De-packagers use characteristics like color, weight, size, shape, density, hardness, magnetism, electrical conductivity, and light refraction to “code” what the de-packaging system passively or actively selects for in the mixed feedstock (Coker, 2019). According to the literature, de-packagers can process about 8–12 tons of feedstock per hour, with some models capable of up to 150 tons/day (Goldstein, 2015; Gorrie, 2015). The most common separation actions employed by de-packagers are shearing, hammering, horizontal or vertical pressure through a screen, or a combination of these (Coker, 2019; Gorrie, 2015). Many de-

[4] Wind sifters use air and suction to remove light materials from screen overflow, which is material that can be returned to compost or digestate as an ideal structure material (Komptech Americas, 2021).

[5] Trommel screens consist of a rotating cylindrical drum and are used for separating materials. When the material enters the drum screen, the material on the screen surface will turn over and roll so that the qualified material will be discharged through the outlet at the bottom of the drum, and the unqualified material will be discharged through the outlet at the end of drum (M&C, 2020).

[6] Star screens include rotating rubber stars that allow fine material to fall through and larger material to be carried across the screen. The motion of the star screen also helps break up material (Toto, 2003).

packager systems use a hopper and conveyor or auger to move the feedstock into a shredder or screw press (Coker, 2019; Gorrie, 2015).

Different models handle plastics better than others that are more adept at handling corrugated cardboard, for example. Lighter materials, like water bottles and fruit packaged in plastic, may float to the top in some models and create a thick layer that does not get ripped open by the chopper at the bottom of the vault (Goldstein, 2015). Styrofoam, or some plastics that become tangled in the auger and need to be cut out (Gorrie, 2015).

De-packagers have two required inputs: food waste and electricity. Certain models require water as well. De-packagers are designed to process a heterogenous mix of packaged food waste including materials like plastic, coated cardboard, and metal cans; however, case studies illustrate that the de-packagers work best with consistent feedstocks. For example, an anaerobic digestion operator in Ontario that processes both industrial packaged food waste and residential source-separated organics, found that residential food waste can be very hard on the de-packaging equipment as it contains a variety of contaminants, and that the more predictable food waste streams from industry are preferable (Gorrie, 2015).

De-packagers have two end products: the recovered organic material separated from its packaging and the captured packaging itself. Different de-packagers can produce different outputs depending on what the final processing will be: wet outputs for use as anaerobic digestion feedstock or dry outputs for composting feedstock.

Recovery and purity are the metrics used to evaluate how effective de-packaging machines are at mechanical separation (Coker, 2019). Recovery is the percentage of food captured from the original packaged food waste feedstock, and purity is the percentage of desired material (as opposed to contaminants) in the final food waste output. While many vendors claim purity and recovery rates of over 99 percent, BioCycle states that food waste de-packagers typically achieve a 90–97 percent purity and recovery rate, depending on how much food waste sticks to the packaging after separation (Coker, 2019). However, no peer-reviewed research was found to confirm these purity and recovery rates, and the contaminant detection methodologies were not provided.

Because de-packaging systems are large and expensive, they are best suited to operations that generate a large amount of packaged food waste (anywhere from 5 to 20 tons per day) and that have sufficient space for the system's installation (Gorrie, 2015; Sullivan, 2012). Although cost information is not readily available for most de-packaging systems, one operator reported spending more than $1 million on its de-packaging system (Gorrie, 2015). The high costs and space requirements of de-packagers may limit the number of commercial food waste generators or others who purchase them.

Photo Credit: Thomas Darby, Water Pollution Control, Hermitage, PA

Prevalence of Contaminant-Removal Techniques

Each of the above techniques is utilized by some composting and anaerobic digestion facilities in the United States. Several recent surveys shed light on removal techniques currently in use:

- A 2018 CalRecycle-funded study found that 32 percent of large composting facilities in California use a picking station to remove contamination and 50 percent use other equipment (CalRecycle, 2019).

- The Washington State Organics Contamination Reduction Workgroup conducted a survey of six major commercial compost facility operators in Washington State, finding that the following contaminant-removal processes were not commonly used at compost facilities: flotation separation, air knives, disc screens, eddy current separation, infrared optical sorting and removal methods, zigzag separation. The surveyed compost facility operators stated they were hesitant to invest in high-cost, unproven technologies because it is unclear whether the addition of these technologies would provide a level of contaminant removal worthy of their investment (i.e., the additional removal provided by these technologies could be minimal) (State of Washington, 2017).

- EPA conducted a survey of U.S. anaerobic digestion facilities in 2017-2018 (U.S. EPA, 2021a, b). Thirty eight percent of digestion and co-digestion facilities reported some form of pre-processing of feedstock on-site. The most commonly used pre-processing activities were grinding (particle size reduction or maceration), screening and/or sorting, manual or mechanized de-packaging/de-bagging, and shredding. Manual and mechanized de-packaging were most commonly used by stand-alone anaerobic digesters, compared to digesters on farms or at WRRF facilities. Third-party pre-processing was also used by some co-digestion facilities (U.S. EPA, 2021a, b).

BioCycle’s research indicates there are currently very few de-packagers in use across the United States (Coker, 2019); however the market is growing, due to the increasing number of anaerobic digestion operations and new state regulations (e.g., in Massachusetts) that require the diversion of commercial organic waste from landfills (Spencer and Casella, 2017; Sullivan, 2012).

The operators of centralized anaerobic digestion and composting facilities are starting to use de-packagers to prepare food waste before it enters their facilities, and some third-party waste haulers that have contracts with large retailers to remove organic waste from their facilities also employ them (Gorrie, 2015). De-packagers are commonly used in Europe, where recovered food waste has grown into a marketable commodity (Gorrie, 2015; Sullivan, 2012).

Effectiveness of Contaminant-Removal Techniques

Mechanical removal approaches can significantly reduce the amount of plastic contamination in food waste used as feedstock; however, the efficiency of these processes at removing plastic contamination is not well documented in the existing literature. Plastic material, including microplastic, has been found in finished compost and digestate, indicating currently used processes are not entirely efficient at removing all plastic (Braun et al., 2020; Weithmann et al., 2018; Zero Waste Scotland, 2016). See Section 4 for discussion of levels of plastic contamination in finished compost and digestate.

When composting and anaerobic digestion facilities use multiple processes—for example, pairing manual picking with de-packaging and screening— or apply removal techniques both pre- and post-processing, the removal rate is likely to increase because fragments of varying sizes will be captured during different processes (Aspray et al., 2019). Facilities often use grinders and shredders to prepare feedstock for composting and anaerobic digestion in addition to manual and mechanical removal processes, and these processes can also impact plastic contamination.

The Washington State Organics Contamination Reduction Workgroup conducted a survey of six major commercial compost facility operators in Washington State to determine the most effective methods for removing common contaminants present in food waste collected for composting. Composters were asked to rate each method or technology on a scale of 1 to 10, based on their experience, according to its overall effectiveness, capital and operating costs, ease of use, and flexibility. Washington State commercial compost facility operators scored airlift separators and picking stations as tied as the most effective contamination-removal methods for low-density materials, with an average score of 7.4 for each. Star screens were ranked the third most effective method, with an average score of 7.25. Other types of separators, including conveyor separation using air and flotation separation, were the fourth most effective method, earning an average score of 6.5 (State of Washington, 2017). These ratings and observations are from one study in Washington and may not be representative of the opinions of compost facility operators across the country. In addition, opinions could vary based on different brands of technologies used and not all contaminant-removal technologies may have been in use at these facilities.

Even if de-packagers remove a majority of plastics from the food waste stream, as reported by BioCycle, the forces used for separation by de-packagers can result in fragmentation of the plastics into smaller pieces (Coker, 2019). This fragmentation may lead to microplastics being introduced into the finished compost or digestate (or contribute to microplastic levels already present in feedstock).

Newer de-packager models are designed to separate the packaging with the least amount of force necessary to minimize splintering of the packaging (Coker, 2019). However, there is little research available to characterize the level of prevention gained.

Other mechanical processes could have a similar effect. In a report by Washington State, compost facility operators indicated that grinders will reduce the size of plastic particles, making it difficult to remove the pieces (State of Washington, 2017).

Fate of Plastics after Manual or Mechanical Separation

After removal from food waste, plastic contaminants are typically transferred to a landfill for disposal (ADBA and REA, 2018). In some instances, rejected material is sent to combustion facilities with energy recovery. At these facilities, combustion is used to generate steam for electricity production. Recovered packaging is often not recyclable due to contamination with food waste (i.e., the output is commingled) (Gorrie, 2015). To be acceptable for recycling, the packaging may require extra cleaning and drying, which is not economically viable (Spencer and Casella, 2017).

Some de-packagers can recover the packaging itself for subsequent recycling. Packaging recovery depends on the mix of packaging types put into the system: homogenous mixes of a single type of packaging make it easier to recover the packaging to reclaim its value, but heterogenous mixes of multiple packaging types make it very difficult to successfully recover the packaging (Sullivan, 2012). For example, large, uniform loads like organics in plastic bottles may be recycled (Gorrie, 2015). Film plastics, however, are not recyclable. Some de-packaging systems use magnets or blowers to direct separated packaging into a collection container that can be hauled away for recycling or landfilling (Gorrie, 2015).

4. PLASTIC CONTAMINATION IN FINISHED PRODUCTS

Compost and digestate, two common products generated from processing food waste, are frequently marketed as soil amendments, such as fertilizers and soil conditioners.[7] Almost all compost is made with end-use quality in mind, whereas digestate produced from anaerobic digestion is more variable, depending on the feedstocks used, and generally has less direct marketability to end users. Facilities can sell soil amendments made from compost and digestate, which used food waste as feedstock, but the overall quality of these products is directly tied to the feedstock used to generate them. Maintaining product quality is key to maintaining market demand for end products, and processors must balance the costs of removing contamination—through increased manual labor and/or new equipment—with maintaining competitiveness (King County Solid Waste Division, 2019a).

Plastic contamination of feedstock tends to be the biggest challenge to end-product quality due to its volume and variability (Aspray, 2016; Harrington, 2015). Despite employing the removal techniques described in the previous section, some plastic remains in finished products. The contamination may include large visible plastics or smaller fragments called microplastics.

4.1. Levels of Plastic Contamination in Finished Products

In some instances, plastic fragments are large and visible, making the "poor quality" of products immediately obvious, whereas meeting other quality criteria requires laboratory analysis (Aspray, 2016). Many compost facility operators report seeing their bright colors in finished compost (Nosowitz, 2018; Harrington, 2015). For example, produce stickers, which are small, thin, sturdy, and water resistant, often pass through screens designed to catch them and do not break down in the composting process (Nosowitz, 2018; Harrington, 2015).

Other plastic materials, including hard and soft plastic containers, bags, and plastic-coated paper products, can break down into smaller pieces while never completely decomposing in finished material (Harrington, 2015). Mixed with compost, these small plastic fragments are hard to see, but after the compost is applied to soil, the fragments can become more visible once rain or irrigation water has washed away some of the organic material (Harrington, 2015). Also, microplastic particles remaining in the compost, which may not be visible to the naked eye, are a potential environmental and human health concern (See discussion in Section 5).

Photo Credit: Doug Pinkerton, BioCycle.net

[7] A soil conditioner is a product added to soil to improve the soil's physical qualities, including its ability to provide nutrition for plants, and sometimes its behavior (e.g., permeability, friction, etc.).

Quantitative data on the levels of plastic contamination in soil amendments made from digestate in the United States was not available in the peer-reviewed literature, but a limited amount of quantitative data on the levels of plastic contamination in compost in the United States is available. Table 3 summarizes the available data.

Hard plastic was found at levels of 0.1 to 0.7 percent by (dry) weight and film plastic was found at levels of 0.0 to 0.7 percent by (dry) weight in compost produced from yard debris composting programs that use either plastic leaf-bag or food waste collection and sieving to remove contaminants (Brinton, 2005). Plastic contamination was found in both the whole (greater than 25 mm) and 4 mm to 10 mm fraction, but the total content in the 4 mm to 10 mm fraction was only 0.35 percent. Less plastic was found in composts generated from yard waste and food waste than in composts generated from MSW (Brinton, 2005).

Compost analysis methods for use by laboratories and compost operators are available in the Test Methods for Examination of Composting and Compost (TMECC) laboratory manual that was jointly published by the U.S. Department of Agriculture and the U.S. Composting Council in 2001. The TMECC provides protocols and benchmark methods for compost analysis of many parameters, including physical contaminants such as plastic. BioCycle reports that the TMECC standards for testing are widely adopted by laboratories across the United States but are not universal (Duprey, 2019). Tests for physical contaminants used in the United States and in some European countries involve screening the compost, manually isolating physical contaminant fragments, and quantifying them on a weight basis (Aspray, 2016). Tests done in the United States are carried out using fresh material, whereas tests done in Germany and in the U.K. use dried or partially dried material (Aspray, 2016).

Tests commonly used in the United States to measure physical contaminants in compost do not account for contaminants less than 4 mm in size (Aspray, 2016) and thus may miss some microplastics (defined as plastic particles <5 millimeters [mm] in size in any one dimension). In addition, the tests for physical contaminants are labor intensive (e.g., require additional sieving and extraction steps) and costly, making it impractical to process large sample sizes in the laboratory (Bläsing and Amelung, 2018). Compost is heterogenous in nature, and physical contamination is a parameter often singled out by compost producers as being especially variable between different samples (Aspray, 2016).

International Data

A limited amount of quantitative data on the levels of plastic contamination in soil amendments made from compost in the United States was available in the peer-reviewed literature and no data is available on levels of plastic contamination in digestate (Brinton, 2005); however, two peer-reviewed articles and several reviews are available from European countries and Australia (NSW EPA, 2019; Brinton et al., 2018; Weithmann et al., 2018; Zero Waste Scotland, 2016). Table 3 summarizes the available quantitative data on the levels of plastic contamination in soil amendments made from compost and digestate.

The available international literature reports a wide variation in the level of plastic contamination found in samples of compost and digestate derived from household and commercial organic waste, ranging from 0 to 0.22 percent by weight (Braun et al., 2020; NSW EPA, 2019; Weithmann et al., 2018; Zero Waste Scotland, 2016). Part of this plastic contamination is microplastic particles, which have been found at levels of 14 to 895 MPs per kilogram (kg) dry weight in compost and digestate (Weithmann et al., 2018). Data on the level of plastic present in the food waste used to generate the products measured in these studies is not reported.

Because raw material mainly influences the plastic contamination of compost (Braun et al., 2020) and digestate, it is important to consider accompanying data on waste stream contamination rates and de-contamination strategies in order to extrapolate to the U.S. context. Based on the available gray literature, the level of plastic contamination in European food waste streams is similar to the levels in the United States (Section 2.2). The plastic contamination rate is 1.5 percent for food waste in Italy, and European stakeholders have supported the use of this rate as a target for other European countries (Bioeconomy Working Group of the European Parliament Intergroup on Climate Change, 2020). In Italy, this low rate of plastic contamination is attributed to the collection of food waste using compostable bags or reusable containers (Bioeconomy Working Group of the European Parliament Intergroup on Climate Change, 2020). Some of the available international literature provide information on the de-contamination strategies used to reduce levels of plastic in food waste processed into compost and digestate. De-contamination strategies include the use of manual (i.e., sorting) and mechanical

TABLE 3. PLASTIC CONTAMINATION RATES IN FINISHED COMPOST AND DIGESTATE

Concentration of Plastics: % Dry Weight	Concentration of Plastics: MPs/kg	Source	Sampling Location	Reference
Food Waste Sampled Outside of the United States				
1.5[a]	–	Food waste	Italy	Bioeconomy Working Group of the European Parliament Intergroup on Climate Change (2020)
Compost Sampled in the United States				
0.0–0.7 (film plastic)	–	Yard debris	United States	Brinton (2005)
0.1–0.7 (hard plastic)	–	Yard debris	United States	Brinton (2005)
Compost Sampled Outside of the United States				
0–0.21	–	Source-separated food	Netherlands, Scotland, and Ireland	NSW EPA (2019)
0–0.21	–	Garden waste	Netherlands, Scotland, and Ireland	NSW EPA (2019)
0.005–0.06	–	Municipal green waste	Germany	Braun et al. (2020)
0.06–0.22	–	Green waste	Netherlands, Scotland, and Ireland	NSW EPA (2019)
0.14	–	Household biowaste	Germany	Braun et al. (2020)
–	20–24	Household organic waste and green clippings	Germany	Weithmann et al. (2018)
Digestate Sampled Outside of the United States				
0–0.04	–	Not specified	Germany	Zero Waste Scotland (2016)
0.1–0.2	–	Food	Wales	Zero Waste Scotland (2016)
≤0.01–0.39	–	Food	United Kingdom	(Aspray et al., 2017)
–	14–146	Household organic waste and green clippings	Germany	Weithmann et al. (2018)
–	895	Commercial organic waste	Germany	Weithmann et al. (2018)

removal techniques (i.e., separators, sifters, screens, sieves) that are also used at U.S. processing facilities (NSW EPA, 2019; Weithmann et al., 2018; Zero Waste Scotland, 2016; JRC, 2014).

The New South Wales, Australia, Environment Protection Authority (NSW EPA) conducted a review of published literature and other information on the compost derived from source-separated food and garden waste (NSW EPA, 2019). The objectives of the review were to characterize the physical, chemical, and biological data on compost produced from food and organic waste internationally; to consult with compost producers around the globe; and to compare compost made from food and garden organic waste with compost made from mixed-waste organic outputs in Australia. The literature review collected data on plastic contamination in compost derived from food and garden waste from six countries (described as mostly European with a limited amount of data from North America). Data reported directly from compost facilities in three countries (Netherlands, Scotland, and Ireland) were also included. Data from the literature were also presented for compost derived from green waste (in this case, organic waste from grass clippings, leaves, etc. but void of food waste).

In the data examined by the NSW EPA review, the range of plastic fragments (larger than 2 mm) was similar in both compost derived from source-separated food and garden waste (0–0.21 percent dry weight) and green waste (0.06–0.22 percent dry weight) (NSW EPA, 2019). As part of its review, the NSW EPA also concluded that mixed-waste organic outputs[8] have a higher percentage of plastic contamination than compost made from food and garden waste or green waste (NSW EPA, 2019). These findings are supported by a separate Europe-wide survey effort from the Joint Research Centre (JRC, 2014). The levels of physical contaminants, including plastic, present in compost made from food and garden waste provided by processors while the survey was conducted were all lower than those for mixed-waste organic outputs. Concentrations of “total impurities” were an order of magnitude lower in these food organic and garden organic waste samples compared with mixed-waste organic outputs (JRC, 2014).

The Scottish Environmental Protection Agency (SEPA) also conducted a review and investigation into plastic contamination in food waste-derived digestate and agricultural soils (Zero Waste Scotland, 2016). SEPA reports that in food waste-based feedstocks sampled between 2013 and 2014, the level of physical contaminants (including plastic and other contaminants) ranged from less than 1 percent to greater than 10 percent on a fresh waste basis; the fraction of this weight attributed to plastic is not reported (Zero Waste Scotland, 2016). Hand picking, de-packaging, screening, shredding, and pulping were used during pre-processing of food waste-based feedstocks to remove plastic and reduce feedstock size (WRAP, 2014). Their review found only limited data on levels of plastic in digestates, including reports of 0.1–0.2 percent dry weight of plastic in food-based digestates in Wales and 0–0.04 percent dry weight of plastic in digestates in Germany (Zero Waste Scotland, 2016).

In addition, SEPA investigated levels of plastic present in digestate produced by four U.K. anaerobic digestion facilities in 2015 and 2016 (Aspray et al., 2017). The range of plastic fragments (larger than 2 mm in size) present in digestate ranged from less than 0.01–0.39 percent dry weight of finished digestate. Lower amounts of plastic contamination were found in finished digestate collected from facilities that used post-processing screening and accepted only high-quality feedstocks (Aspray et al., 2017).

Weithmann et al. (2018) investigated the level of microplastic particles (1 to 5 mm in size) in samples of finished composts and digestates from four facilities in Germany. Sieving and sifting procedures are commonly used to significantly reduce the amount of plastic in incoming household organic waste and green clippings. Weithmann et al. (2018) report that the typical final processing step for compost (presumably at German facilities, though not specified by the authors) includes sieving using mesh sizes that range from 8 to 15 mm. The use of these mesh sizes would allow particles smaller than 5 mm to pass through these sieves and enter the compost. In this investigation, samples of finished composts and digestates were gently fractionated using sieves with mesh sizes that range from 5 mm to 0.5 mm and most plastic particles measured between 2 mm and 5 mm in size. Despite the use of these de-contamination strategies, compost derived from household organic waste and green clippings contained 20 to 24 microplastic particles per kg of compost. Digestate derived from household organic waste and green clippings contained 14 to 146 microplastic particles per kg of digestate, whereas digestate from a facility

[8] Note that a specific definition was not provided for “mixed-waste organic outputs.” However, this term appears to refer to non-source separate organic material (NSW EPA, 2019).

processing solely commercial organic waste contained 895 microplastic particles per kg of digestate (Weithmann et al., 2018).

Braun et al. (2020) investigated the levels of plastic and microplastic particles in composts from two facilities in Germany. One facility produced compost derived from biowaste from households (not further defined but assumed to include food waste), and the other facility produced compost derived from municipal green waste (described as green cuttings). All the 40 compost samples contained plastic in detectable amounts except for one, but the levels were highly variable between samples (as indicated by large standard deviations). Compost derived from household biowaste contained on average 1,358 ± 596 milligrams (mg) of plastic per kg of compost (corresponding to 0.14 percent dry weight), with the majority of fragments classified as mesoplastic (5 to 25 mm in length). Microplastic particles (less than 5 mm in length) made up on average less than 10 mg/kg of the compost derived from household biowaste. Plastic contamination was lower in the compost derived from municipal green waste, with average plastic content varying from 48 to 622 mg/kg (corresponding to 0.005 to 0.06 percent dry weight) (Braun et al., 2020).

4.2. Effect of Plastic Contamination on Value and Use of Finished Products

Compost facility operators in Washington have reported that feedstock contamination has made finished products difficult to market (State of Washington, 2017). The quality of finished products generated using food waste has been too poor in some instances for the finished products to be sold for agricultural land application. In these instances, the products are likely to be sold (at a lower price) for other applications, such as landscaping and roadside projects, or sent to a landfill to be used as alternative daily cover (Sardarmehni et al., 2021; King County Solid Waste Division, 2019a; Alexander, 2017). These applications may provide more limited environmental value.

A 2018 CalRecycle-funded study found that 30 percent of large composting facilities in California were deeply concerned about contaminated feedstocks; 16 percent said contaminated products have limited markets; 38 percent said they avoid contamination by not accepting food scraps; and only 4 percent reported no issues with contamination (CalRecycle, 2019).

The literature does not indicate whether ineffective removal is happening with high frequency at U.S. composting or anaerobic digestion facilities, resulting in unused products. However, facility operators are concerned about the cost and effectiveness of contamination-removal strategies and their ability to produce quality, marketable products (CalRecycle, 2019; King County Solid Waste Division, 2019a; State of Washington, 2017).

Challenges with producing finished material adequate for land application have also been reported at anaerobic digestion facilities in Toronto, Canada, and in Barcelona, Spain, which operate with source-separated organics (Arsova, 2010). Several processes—including dry mechanical pretreatment with a sieving drum (>120 mm) and wet mechanical pretreatment of suspensors with a sieving drum, designed to remove plastic and other contamination—proved to be ineffective at separating contaminants from feedstock. These processes resulted in the transfer of large amounts of rejected material to landfills (Arsova, 2010).

Industry standards and regulatory measures have been implemented in many countries and U.S. states to support the manufacture of quality compost and digestate (discussed in Section 6); however, there is no clear consensus on what constitutes an acceptable level of plastic contamination.

Plastic contamination presents a barrier to the use of processed food waste products when the level of contamination warrants the rejection of finished material from sale or use in favor of landfilling or another disposal method. If more food waste is to be collected and processed into products like compost or digestate, the feedstock used to make them must be of high quality with plastic contamination levels that can be adequately managed by processors. If it is not feasible to attain this quality, these products will hold little to no value as they are not preferred for land application.

5. RISKS TO ENVIRONMENT AND HUMAN HEALTH

As food and food packaging and containers become “waste” they must go somewhere. Therefore, risk should be examined not only as an absolute, but rather relative to the risk of other potential pathways for food waste. This section examines the potential risks to human health and the environment of land applying plastic-contaminated compost and digestate made from food waste, as well as managing plastic-contaminated food waste streams in other ways, such as sending it to a landfill, incinerator, or down the drain into the sewer system.

While quantitative analyses of exposure and risk comparing these options are not available to determine whether one option presents less risk than the others to human health and the environment due to plastic contaminants, some general observations about plastic exposure pathways, exposure levels, and potential risks are presented below. Broader environmental impacts (e.g., greenhouse gas emissions) and benefits (e.g., energy generation and soil enhancement) for each option are not discussed here.

5.1. Application of Soil Amendments Made from Food Waste

Plastic particles, including microplastics, have been shown to remain in soil amendments produced using finished compost and digestate derived from food waste. This contamination poses potential risks to the environment and human health when those products are applied to land. Quantitative analyses of exposure and risk associated with plastic in the food waste stream after processing are not available. More quantitative information about the levels of plastic in food waste streams and products made from compost and digestate (particularly in areas where regulatory limits for plastic present in finished material have not been established) are needed before exposure can be thoroughly assessed. Understanding potential pathways of exposure and the exposure levels associated with these pathways are an important piece of the risk analysis. Some general conclusions about exposure pathways and potential risks to the environment and human health are presented in this section.

As discussed in Sections 3 and 4, for food waste streams accepted for processing through composting or anaerobic digestion, the available literature offers consensus that: (1) not all plastic is removed before processing, and (2) plastic fragments of varying types and lengths are present in finished compost or digestate. Given removal approaches typically used by processing facilities, the number of smaller fragments or microplastics present in finished materials is likely larger than the number of larger fragments, though typical levels corresponding to these categories are not well documented in the literature. Some mechanical processes (most commonly shredders, grinders, and de-packagers) grind or pulverize plastic material into smaller pieces or microplastics. Microplastics can therefore remain in food waste that is moved forward for additional processing into finished material, such as compost or digestate.

Soil amendments made from compost and digestate are used in agriculture, gardening, landscaping, and other applications because they are rich in organic matter and nutrients that are slowly released into the soil over a longer period compared with the quick release of nutrients from petroleum-based chemical fertilizers. They are beneficial to soil quality when applied at appropriate rates.

When soil amendments that contain plastic contamination are applied to land, plastic fragments (including microplastics) are released to the environment (Weithmann et al., 2018). Microplastic particles in the environment have been shown to degrade into nanoplastic particles (generally defined as less than 100 or 1,000 nanometers in at least one of its dimensions) (Brachner et al., 2020; Wang et al., 2020). While microplastics in soils are not expected to be taken up into the roots of plants, nanoplastics that are formed by the degradation of these microplastics might be taken up by plants (Golwala et al., 2021).

After land application, plastic fragments in soil amendments can have direct impacts on the health of the soil to which they were added by changing the properties of the soil (e.g., texture and structure) and impacting plant performance (de Souza Machado et al., 2019; de Souza Machado et al., 2018). In large quantities, plastic contamination may affect physical properties of compost-amended soil, such as soil coloring, heat retention, and drainage (CalRecycle, 2016). Changes to the soil environment, including bulk soil density and water availability, were observed after adding microplastics (fragments of HDPE, PET, polypropylene, or polystyrene ground to fragments <1 mm in length) to experimental soils used to grow spring onions (de Souza Machado et al., 2018). The presence of microplastics in soil also resulted in increases or decreases to root biomass and area, leaf biomass, water content, and leaf nitrogen content (de Souza Machado et al., 2018). Consequences of these alterations included changes to water cycling, plant-soil feedbacks, and soil microbial diversity (de Souza Machado et al., 2019).

Plastic fragments in soil amendments might also be distributed into the greater environment when carried by both wind and surface water run-off to other soil and terrestrial and aquatic environments (Brinton et al., 2018). Weathering[9] of microplastics in the environment also impacts their transport and distribution and influences sorption and aggregation between microplastics and other environmental constituents (Duan et al., 2021). Once plastic fragments have been released into the environment, their recovery is nearly impossible (Brinton et al., 2018). Because of their small size, microplastics enter the food web and have been found in human food including seafood (Toussaint et al., 2019). Microplastics also have been identified in tap water and bottled water across several countries (OECD, 2018).

The ecotoxicological effects of microplastics and nanoplastics on marine invertebrates, phytoplankton/zooplankton, and plants have been demonstrated in many studies and include chronic adverse effects on feeding, growth, and reproduction (Wang et al., 2020; Yong et al., 2020). More research is needed to understand the terrestrial fate of micro- and nanoplastics and their potential adverse effects on soil, freshwater, and terrestrial ecosystems (Kumar et al., 2021; Wang et al., 2021; Kumar et al., 2020; Bradney et al., 2019; de Souza Machado et al., 2018). Limited experimental evidence has shown that microplastics and nanoplastics have the potential to produce toxic effects in some terrestrial organisms (Kumar et al., 2020; Bradney et al., 2019; de Souza Machado et al., 2018). For example, invertebrate studies indicate that microplastics can act as a vector of toxic zinc present in soil in earthworms and inhibit growth and reproduction in both the collembolan Folsomia candida and the freshwater crustacean Daphnia galeata (Wang et al., 2021; Dong et al., 2018; Hodson et al., 2017; Huerta Lwanga et al., 2016). The potential toxicological effects of micro- and nanoplastics on humans and other mammals remain largely unclear (Yates et al., 2021; Yong et al., 2020). Available rodent in vivo and human in vitro studies have demonstrated that nanoplastics can have adverse effects on the immune system (Wang et al., 2021).

Organic pollutants in the environment can become adsorbed onto micro- and nanoplastic particles (Atugoda et al., 2021; Wang et al., 2020; Yong et al., 2020). Plastic fragments have been shown to adsorb persistent organic pollutants (POPs), including polychlorinated biphenyls, dichlorodiphenyl trichloroethane, hexachlorobenzene, and nonylphenol, which have accumulated in the surrounding environment (Mato et al., 2001). However, the thermophilic temperature characteristic of the composting process seems to be effective in removing volatile compounds while microbial reactions are effective at removing labile compounds. During the maturation phase in composting, some POPs become immobilized as they bind to organic matter reducing their bioavailability in the short term (Thakali and MacRae, 2021).

Microplastics in the marine environment have been shown to concentrate POPs, which have a greater affinity for the surface of plastic compared with seawater (Wright et al., 2013). Microplastics are more likely to transport POPs than bigger pieces of plastic because of their larger surface area-to-volume ratio (Browne et al., 2009). Microplastics are also easier for marine organisms to consume than larger plastic pieces.

In addition, plastic used for bags, food packaging, and containers is manufactured using various chemical additives, including plasticizers (e.g., phthalates), antioxidants (e.g., phenols), and stabilizers (Geueke et al., 2018). In addition, these plastic materials, especially post-consumer recycled materials, may contain degradation products of additives and contaminants such as heavy metals and brominated flame retardants (Geueke et al., 2018). The topic of persistent organic chemical contaminants in food waste streams is discussed in a separate issue paper prepared by EPA and is outside of the scope of this paper.

[9] Weathering processes include mechanical fragmentation, photo-degradation, thermal-degradation, and biodegradation (Duan et al., 2021).

The available literature does not provide substantial evidence of environmental or human health effects that are occurring as a result of plastic contamination in finished compost and digestate products; however, there are questions and concerns regarding the release of micro- and nanoplastics into the environment as a consequence of the grinding and shredding that occurs at processing facilities and the breakdown of larger plastic fragments in the soil over time.

5.2. Other Food Waste Management Pathways

When soil amendments made from compost or digestate are applied to land (e.g., as a source of nutrients), these plastic fragments and microplastic particles enter soil and water posing potential risks to both the environment and human health (Weithmann et al., 2018). It is important to consider this issue in context, however. If the plastic-contaminated food waste is not processed through composting or anaerobic digestion, it will likely be (1) landfilled, (2) incinerated, or (3) sent “down the drain” through the sewer (either with or without processing by a garbage disposal or other grinder), which may all also pose risks to human health and the environment.

Food waste is most commonly landfilled in the U.S. Human exposure to plastic found in landfills is assumed to be low as these facilities are subject to the requirements of the Resource Conservation and Recovery Act, including liners, leachate collection and monitoring, and daily cover.

Food waste that is not collected for processing or thrown away in the trash (and sent to landfill) is often disposed of “down the drain.” Plastic that is sent down the drain with food waste (e.g., produce stickers) can enter building drains and sewer systems directly or after being ground by garbage disposals. When food waste is sent down kitchen drains, it either goes into site-specific septic systems and leach fields or it makes its way into the wastewater stream to be processed by a WRRF. Once food waste is washed down the drain, it is treated like all other sewage in WRRFs or septic facilities. Wastewater recovery plant effluent is typically discharged to a nearby waterbody.

There is evidence that WRRF effluent can be a source of microplastics in the environment (Tang et al., 2020). One study found that the majority of microplastics detected in wastewater effluent could be attributed to fragments of PVC (Tang et al., 2020). Although PVC is used to manufacture food packaging, such as clamshell containers, trays, caps, lids, egg cartons, loose fill, produce baskets, coatings, and closures, it is also commonly used in personal care products, stretchable polyester fabrics, and in sewage pipes (Tang et al., 2020). Therefore, the contribution of food packaging to the level of microplastics present in wastewater effluent is unclear.

In the United States, EPA issues National Pollutant Discharge Elimination System permits that contain limits on what can be discharged, monitoring and reporting requirements, and other provisions to ensure that the discharge does not impair water quality for humans or aquatic life.[10] EPA asserts that the toxicity risk to marine organisms from ingesting microplastics and POPs that cling to them, or from consuming prey that has consumed microplastics, requires further study (U.S. EPA, 2020e). EPA has stated that microplastics and POPs may be a contributing stressor to sensitive species in some of the world’s ocean and coral ecosystems, and EPA is acting under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) to assess and mitigate this threat to the environment and human health (U.S. EPA, 2020e).

5.3. Comparing Food Waste Management Pathways

Quantitative estimates of exposure and risk associated with exposure to plastic contaminants, including any chemical additives—present in food waste sent to landfills, processed and applied to land as compost or digestate, or sent to WRRFs after being sent down the drain—are not available at this time. It is clear, however, that some environmental and human exposure to plastic fragments, including microplastics, is likely after processed food waste is applied to land or discharged to the environment as wastewater recovery plant effluent.

[10] When developing effluent limitations for an NPDES permit, a permit writer considers both the technology available to control the pollutants (i.e., technology-based effluent limits) and limits that are protective of the water quality standards of the receiving water (i.e., water quality-based effluent limits). Therefore, the pollutants included in the permit are contingent on whether receiving body water quality standards exist for a particular pollutant.

Higher levels of exposure are likely to occur (1) in areas where no regulatory limits are in place on the amount of plastic contamination permitted in finished compost or digestate, (2) when the plastic fragments present in finished material are microplastics, and (3) when finished material containing plastic is applied to land rather than landfilled.

Risks to the environment and human health are assumed to increase as the number of exposure pathways increases along with the level of exposure associated with each of these pathways. If chemical additives are present and can leach from the plastic, their environmental fate will be driven by chemical-specific properties. As a result, the potential environmental exposures are likely to be different from those of the plastic particles.

5.4. Levels of Plastic Contamination in Background and in Other Land Applied Products

When data on plastic contaminant levels and particle sizes are available for finished composts in the U.S., it would be helpful to determine the relative magnitude of this contamination when compared to (a) background levels in the soil and (b) other common sources of microplastics for agricultural lands, including biosolids from WRRFs that are currently land applied, polymer-based fertilizers, and wastewater irrigation (Guo et al., 2020; Kumar et al., 2020). This would help policymakers and other stakeholders determine whether further investigation is warranted.

6. STANDARDS AND REGULATIONS

Industry standards and regulatory measures have been implemented in many countries to support the manufacture of quality compost and digestate products. Trade associations (e.g., U.S. Composting Council) and standards organizations (e.g., the British Standards Institution) have established voluntary industry standards for compost and anaerobic digestates that have been adopted by many producers. These standards often specify upper limits for physical contaminants (such as plastic, glass, or metal) in addition to pathogens, heavy metals, and certain toxic chemicals. In addition, some countries, U.S. states, and local governments have enacted regulatory limits for specific contaminants in compost and digestate, especially for products intended for use in agriculture.

In some cases, regulatory limits for plastic contamination have been established for compost and digestate used as fertilizers and soil conditioners. Table 4 summarizes available U.S. and international regulations specific to total physical contaminant and/or plastic limits. These are typically weight-based limits, with a size threshold for particles. Some of these regulatory limits include specific values for film plastics, which tend to have a significantly lower weight-to-surface-area ratio compared with most other physical contaminants (Aspray, 2016).

It is important to note that no regulations were identified regarding limits for plastic fragments with a size of less than 1 mm, and most of the U.S. regulations are specified for fragments greater than 4 mm. These thresholds may be driven by detection levels of widely available in-field and laboratory test methods, akin to the measurement limitations described in Section 2.2., rather than a determination of risk. Information is not available in the literature to determine how often regulated compost and digestate products fail to meet the standards in the United States.

Photo Credit: Assaf Sadeh, Soil Control Lab

TABLE 4. REGULATORY LIMITS FOR PLASTIC CONTAMINATION IN FINISHED COMPOST AND DIGESTATE

Location	Recycled Organic Waste Product	Weight-Based Limit for Total Physical Contaminants[a]		Weight-Based Limit Specific for Plastics		Weight-Based Limit Specific for Film Plastics	
		%	Particle Size	%	Particle Size	%	Particle Size
United States							
North Carolina	Compost	6	–	–	–	–	–
New Hampshire	Compost	2	–	–	–	–	–
New York	Compost	2	–	–	–	–	–
South Carolina	Compost	2	–	–	–	–	–
Iowa	Compost	1.5	<13 mm	–	–	–	–
Montana	Compost	1	–	–	–	–	–
Rhode Island	Compost	1[b]	–	–	–	–	–
Wisconsin	Compost	1	–	–	–	–	–
Minnesota	Compost	3	>4 mm[#]	–	–	–	–
Maryland	Compost	2	>4 mm[#] and <13 mm	–	–	2	>4 mm[#]
Washington	Compost	1	–	–	–	0.25[c]	–
Ohio	Compost	1	>4 mm[#]	0.25	>4 mm[#]	–	–
California	Compost and/or Digestate	0.5	>4 mm[#]	–	–	0.1	>4 mm[#]
Outside United States							
British Columbia, Canada	Compost	1	–	–	–	–	–
Scotland, UK[d]	Compost	0.25	>2 mm[#]	0.06	>2 mm[#]	–	–
Ontario, Canada	Compost	–	–	0.5	–	–	–
Austria	Compost	–	–	0.2	>2 mm[#]	–	–
England, Wales, N. Ireland, UK[d]	Compost	0.25	>2 mm[#]	0.12	>2 mm[#]	–	–
Australia[d]	Compost	0.5	–	–	–	0.05	–
Scotland, UK[e]	Digestate	0.0032–0.0288[f]	>2 mm[#]	–	–	–	–
England, Wales, N. Ireland, UK[d]	Digestate	0.04–0.36[f]	>2 mm[#]	–	–	–	–
European Union	Compost and digestates used as soil conditioners or fertilizers	0.3 (applies in 2022); 0.25 (applies in 2026)	>2 mm[#]	–	–	–	–
Austria	Fertilizer	–	–	0.1	>2 mm[#]	–	–
Germany	Fertilizer	0.4	>1 mm[#]	–		0.1	>1 mm[#]

includes microplastic particles. Microplastic particles are plastic particles <5 millimeters (mm) in size in any one dimension.
[a] Physical contaminants include materials categorized as foreign matter and manmade inerts; particle size provided when specified.
[b] Class A compost.
[c] Must be labeled unless < 0.1%.
[d] These limits are based on standards developed by nongovernmental standards organizations and are not stipulated by regulation; however, if the limits are not met, environmental regulations specify that exemptions/permits are required before using the products.
[e] These limits are enforced by Scottish Environment Protection Agency.
[f] Depending on the nitrogen content.

6.1. Standards and Regulations in the United States

In the United States, fertilizers and soil conditioners are regulated primarily at the state level (TSG Consulting, 2020; Alexander, 2013). U.S. EPA regulations apply only to composts that contain sewage sludge, biosolids, or septage as part of 40 CFR Part 503 Biosolids Rule. The U.S. Composting Council's Seal of Testing Assurance Program sets forth voluntary industry standards for compost, but plastic is not one of the contaminants analyzed (USCC, 2020b).

Figure 1 illustrates the thirteen U.S. states that have regulations specifying the weight-based limit for total physical contaminants, foreign matter, or manmade inerts in compost. One state, California, has a similar limit for digestate. Plastic is categorized as a physical contaminant within these regulations, but only the following four states specify regulatory limits for plastic or film plastics permitted in finished compost or digestate:

- California established that, effective in 2018, finished compost and/or digestate applied to land must not contain more than 0.5 percent by dry weight of physical contaminants greater than 4 mm, and no more than 0.1 percent shall be film plastic greater than 4 mm (State of California, 2018).
- Washington limits the level of film plastic in compost to 0.25 percent by weight and a label or information sheet must be provided with compost that exceeds 0.1 percent by weight of film plastic (State of Washington, 2011).
- Maryland film plastic greater than 4 mm is limited to 2 percent by dry weight in compost (Maryland Department of Agriculture, 2020).
- Ohio limits plastic greater than 4 mm to 0.25 percent by dry weight in compost (Ohio EPA, 2018).

The compost regulations of these four states provide limited information on how the states determine compliance with the regulations and methods that are used to determine the level of physical contamination. No data was available on the amount or frequency of compost not meeting these standards.

Some states require laboratory analysis of samples, while others allow for simple testing using sieves. California's regulation states that the operator of a "compostable material handling operation or facility" shall sample every 5,000 cubic yards of compost produced and determine the percentage of physical contaminants greater than 4 mm using "a method that provides accurate results" and has been approved by the local enforcement agency (State of California, 2018). The methods approved for determining physical contaminants and film plastic content are not described. If an enforcement agency has reason to believe, based on their own visual inspection or otherwise, that a determination of physical contaminants is not accurate, the agency may require that a sample of compost be taken in the presence of an enforcement agent and sent to a laboratory for testing. It is the responsibility of the property owner applying compost or digestate to the land to provide verification of regulatory compliance to the enforcement agency (CalRecycle, 2018). This verification can be information provided by a supplier or other party.

Washington's regulation states that composting facilities must test a representative sample of compost for every 5,000 cubic yards of compost produced using a sampling method similar to those described in the U.S. Composting Council 2002 Test Methods for the Examination of Composting and Compost (Method 02.01-A through E) and adhering to additional parameters, including limits for total physical contaminants and film plastic. The regulation does not specify what methods are approved for determining physical contaminants and film plastic content. The facilities must maintain records of results of analyses that must be available to the jurisdictional health department upon request. If the compost exceeds 0.1 percent film plastic by weight (but not the 0.25 percent limit), a label or information sheet must be provided with the following statement, "This compost does not meet Department of Ecology standards for film plastic content for unrestricted use. This compost may only be used in locations where a means of removing or containing the film plastic on-site is put in place promptly after use. Acceptable controls include removal from the site, incorporation, planting, covering with soil or another media, or containment in a compost sock or similar device. This product may not be used adjacent to regulated waters of the state (e.g., wetlands, streams, lakes) or in environmentally sensitive areas" (State of Washington, 2011).

Maryland's regulation states that samples of compost to be distributed must be analyzed by the facility for each of the specified quality parameters, including film plastic content. The regulation does not specify what methods are approved for the analyses. The Maryland Department Agriculture or a designee may examine records and may inspect and sample any compost or compost product of any producer or distributor to determine whether the records or compost complies with the requirements of the regulation. A sample or lot found to be out of conformity with the regulations shall be subject to a penalty or stop-sale order (Maryland Department of Agriculture, 2020).

Ohio's regulation briefly describes the method that should be used by compost facility operators to determine the percent foreign/inert matter, which includes plastic. The owner or operator of a facility shall obtain a composite sample from each compost pile no greater than 10,000 cubic yards and demonstrate that concentration limits are not exceeded for each of the quality parameters. The regulation states, "Foreign matter content shall be determined by passing a dried, weighed sample of not less than one hundred grams of compost through a U.S. standard No. 5 sieve (four millimeter). The material remaining on the screen shall be inspected and the foreign matter shall be separated and weighed. The weight of the foreign matter divided by the total weight of the compost sample and multiplied by one hundred shall be the per cent dry weight of the foreign matter content" (Ohio EPA, 2018). All records including results of analyses shall be made available for inspection by the approved board of health or Ohio EPA during normal operating hours or when requested.

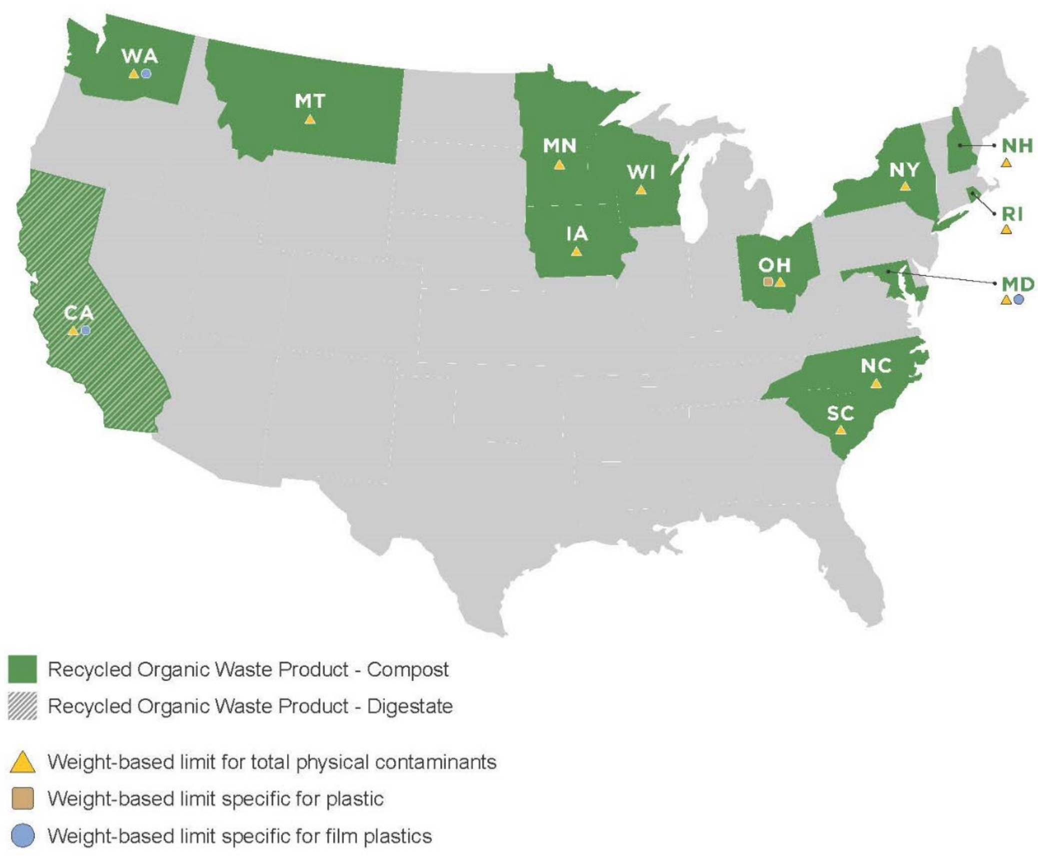

FIGURE 1. STATE REGULATORY LIMITS FOR PLASTIC CONTAMINATION IN FINISHED COMPOST AND DIGESTATE IN THE UNITED STATES

6.2. International Standards and Regulations

The European Union Fertilising Products Regulation specifies criteria for compost and digestate that can be used in organic fertilizers, soil improvers, and growing media. These rules, published in 2019, will go into effect in July 2022 (Stubenrauch and Ekardt, 2020). For both composts and digestates, macroscopic impurities larger than 2 mm (including plastic, glass, or metal) shall not exceed 3 g per kilogram (kg) of dry matter (equivalent to 0.3 percent), and this limit value will be lowered to 2.5 g per kg of dry matter (0.25 percent) in 2026. The sum of all macroscopic impurities shall not exceed 5 g per kg of dry matter (0.5 percent). Plastic particles smaller than 2 mm are not covered by the regulation, and a distinction is not made between hard plastic and film plastic (EU, 2019).

Some European countries have separate regulations apart from those set forth in the European Union Fertilising Products Regulation. Germany reportedly has one of the strictest regulations on fertilizer quality worldwide (Weithmann et al., 2018). The German Fertiliser Ordinance (DüMV) was amended in 2019 to cover all macroscopic impurities, including plastics larger than 1 mm, a change to the previous threshold of 2 mm (Stubenrauch and Ekardt, 2020). A distinction is made in the regulation between hard plastic and deformable foil-like plastic. The limit for very light, deformable foil-like plastics in fertilizers and soil conditioners is 0.1 percent by weight of dry matter (reduced from 0.5 percent in 2017), and for all other macroscopic impurities, including hard plastics, the limit is 0.4 percent by weight of dry matter. In Germany, the (legally nonbinding) limit for deformable plastics is even lower for certified quality composts in accordance with the Federal Compost Association, which limits deformable plastic to only 0.01 percent of dry matter (Stubenrauch and Ekardt, 2020). In Austria, plastic particles larger than 2 mm are limited to 0.1 percent dry matter in fertilizer and 0.2 percent dry matter in compost for agricultural applications (Meixner et al., 2020).

In the United Kingdom, an environmental permit or exemption is needed to spread materials on agricultural land if they do not comply with the relevant Quality Protocol (NIEA, 2014, 2012). The Quality Protocols that apply for England, Wales, and Northern Ireland require that compost and anaerobic digestates meet the British Standards Institution’s Publicly Available Specifications (PAS). PAS 100 applies to compost and PAS 110 to anaerobic digestates. According to PAS 100, total impurities larger than 2 mm (including glass, metal, plastic, other non-stone fragments) are limited to 0.25 percent by weight of dry matter in compost for general use and plastic is specifically limited to 0.12 percent. The limit for physical contaminants greater than 2 mm in digestates is based on the nitrogen content of the digestate and varies from 0.04 percent to 0.36 percent by weight of dry matter (Zero Waste Scotland, 2016). Since December 2019, the Scottish Environment Protection Agency (SEPA) requires stricter quality standards for these materials; plastic in compost is limited to 0.06 percent by weight, and physical contaminants (including plastic) in digestates are limited to 0.0032 percent to 0.0288 percent by weight depending on the total nitrogen content of the digestate (SEPA, 2017a, b).

Australia has a voluntary quality standard for composts, soil conditioners, and mulches—Australian Standard AS 4454-2012—which limits physical contaminants (glass, metal, rigid plastics) to less than or equal to 0.5 percent (w/w) and light, flexible, or film plastics to less than or equal to 0.05 percent (w/w) (South Australia EPA, 2019). Similar to the situation described for the U.K., the quality standard is developed by a nongovernmental standards organization. However, composts and soil conditioners that meet the requirements of the standard are regarded as a genuine product and not a waste, and therefore are not subject to waste regulations and can be used without exemption. Compost and soil conditioners that do not meet the requirements of the quality standard must get exemptions to be used and may only be allowed for specific uses (Victoria EPA, 2017).

The Canadian Fertilizers Act and Fertilizers Regulations apply to compost and products containing compost, but plastic is not specifically mentioned in the regulations and a limit is not specified for physical contaminants (Canadian Food Inspection Agency, 2018). The Canadian Council of Ministers of the Environment (CCME) has published voluntary Guidelines for Compost Quality (CCME, 2005), and most Canadian provinces base their compost quality requirements on the CCME guidelines (Hébert, 2012). The guidelines stipulate that compost shall contain “no more than one (1) piece of foreign matter greater than 25 mm in any dimension per 500 mL” (CCME, 2005). No specific limit exists for plastic. In British Columbia, foreign matter content (e.g., metal, glass, plastic, rubber, leather) in recycled organic matter products is limited to 1 percent of dry weight (Government of British Columbia, 2019). In Ontario, plastic cannot exceed 0.5 percent of the dry weight of compost (Ontario Ministry of the Environment, 2016).

6.3. Comparing U.S. and International Standards and Regulations

Regulatory limits for plastic and/or total physical contaminants in finished compost and digestate, established by various countries and U.S. states, do permit the presence of some plastic in finished material and sometimes also regulate the presence of microplastics. The basis for these regulatory limits of plastic contamination in compost and digestate and their ties to specific human health and environmental concerns are not clear. In some cases, aesthetic concerns (CalRecycle, 2016) and the capabilities of common screening and detection methodologies influenced standards.

Given that many of the regulatory limits for physical contaminants and plastic are specified for particles larger than a certain size (e.g., greater than 1, 2, or 4 mm), compliance could be achieved by reducing the size of plastic fragments in the compost or digestate through additional grinding—thereby decreasing the amount of larger plastic particles but increasing the amount of smaller particles that are present in the compost or digestate.

Overall, the regulations in the United States do not typically address plastic fragments less than 4 mm, and regulations identified for other countries do not address sizes smaller than 1 mm. Recent regulatory actions in the EU and specific European countries have resulted in the lowest limits identified for plastic contamination in recycled organic waste products. In the United States, the strictest limits have been enacted in California, where the limit for film plastics (0.1 percent) is the same as in Germany; however, the German regulation specifies that smaller plastic fragments must be analyzed.

Scotland has set the most aggressive weight-based limit for total plastic in compost at 0.06 percent, whereas Australia has set the lowest standard for film plastics at 0.05 percent by weight. It is unclear whether the overall problem of plastic contamination in processed organic waste products is larger, smaller, or similar in other countries compared with the United States.

7. PREVENTING PLASTIC CONTAMINATION

Processing food waste without contaminants supports the creation of high-quality products that contribute to a sustainable U.S. food system. Preventing plastic contamination before food waste is collected may be more effective at reducing contamination than removing plastic during processing but a coordinated effort among stakeholders is required (State of Washington, 2017). In addition, prevention avoids risks of creating smaller plastic pieces (e.g., microplastics) through mechanical removal techniques.

Several approaches, many of which include participation from and collaboration between the various stakeholders, have been proposed to prevent the introduction of plastic contamination into food waste streams collected for processing, and some are being implemented. As discussed further below, these approaches include:

- Education and outreach campaigns targeting consumers, food service providers, and processors (i.e., composting and anaerobic digestion facilities);
- Cart-tagging programs by haulers and local jurisdictions;
- Well-defined hauler contracts;
- Stakeholder meetings and events with supply chain vendors, commercial end users, and cities;
- Efforts by the food industry; and
- Local ordinances.

7.1. Education and Outreach Campaigns

Education and outreach campaigns provide a suite of messages, tools, and materials to help target audiences increase how much of their food waste is recycled and how much plastic is separated from food waste collected for processing (State of Washington, 2017; Harrington, 2015). These education and outreach campaigns typically include a defined audience, goals, objectives, desired behavior change, and value proposition. Target audiences can include consumers/households, food service providers, and processors (i.e., composting and anaerobic digestion facilities).

The State of Washington (2017) provides an example campaign that targets single-family and multifamily households with a goal to increase composting and exclude non-compostable materials, such as plastics, from containers designed for collection of compostable materials (State of Washington, 2017). To achieve this behavior, consumers are taught about the issues that plastic contamination in food waste can create for composting and anaerobic digestion facilities.

Other outreach campaigns might target food service providers to discourage the purchasing of mixed material types (e.g., a compostable cup with a non-compostable lid or straw), which greatly increases the likelihood of incorrect disposal of plastic materials by consumers (State of Washington, 2017). Guidelines and campaigns targeting processors might focus on gaining information on the types, brands, and amount of plastic contamination in their facilities (State of Washington, 2017).

Disadvantages of education and outreach campaigns are that they can be resource intensive (and jurisdictions often have limited budgets) and a common set of metrics of success is currently lacking (State of Washington, 2017). In addition, participant follow-up to track long-term behavior changes and reporting on the success (or lack thereof) of these campaigns is limited in the available literature. These efforts have had mixed success and may require adjustments to messaging and communication over the course of the campaigns, which will require additional resources. For example, the State of Washington implemented an effective outreach campaign in the 1990s to eliminate the use of plastic bags for collection of yard trimmings. Leveraging the success of that effort, the state implemented a separate campaign to reduce the amount of plastic in food scraps collected for processing (Coker, 2016). Contamination of food scraps did not decrease over the course of this campaign though, which was unlike the outcome from the earlier campaign for plastic lawn and leaf bags (Coker, 2016). Composters in Washington State thus adopted contamination surcharge fees instead (Coker, 2016). Consequently, an education and outreach subcommittee was formed to create a more sophisticated campaign that included segmentation of the audience, development and testing of common and effective messaging and communication tactics, and creation of a tool kit with tested and recommended strategies to reduce contamination in organics, among other strategies (State of Washington, 2017; Coker, 2016). The success of this modified campaign has not yet been reported.

7.2. Cart-Tagging Programs

Some municipalities and haulers have used cart-tagging programs that incorporate consistent, audience-focused education. As part of a cart-tagging program, haulers or other individuals inspect carts designated for collecting food waste to ensure that carts' contents meet the requirements for processing agreed upon by the waste management entity and the processing facility. Carts that contain an unacceptable level of contaminants (which vary among waste managers and facilities) are "tagged" and the contents of that cart are not collected for processing. Although household food waste can be dense, making it difficult for waste haulers to spot contaminants, cart tagging can be used to educate those collecting food waste for processing and as the first step in enforcement.

According to the Washington State Organics Contamination Reduction Workgroup, these programs generally have been found to be an effective and efficient tool for changing participant behavior, enforcing contracts, and minimizing contamination (State of Washington, 2017). Cart tagging requires enforcement, however, to be effective. Although the criteria for cart tagging often exists in current solid waste management and hauling contracts, the provisions may not be enforced regularly or consistently by solid waste management agencies, haulers, and their drivers (State of Washington, 2017).

To assess the effectiveness of cart tagging and investigate any challenges presented by this program, a Washington State Organics Contamination Reduction Workgroup designed a cart-tagging pilot study in the City of Kirkland, Washington (State of Washington, 2017). During the course of the study, waste collection drivers checked 17,020 single-family residential waste carts and 936 commercial and multifamily carts containing materials intended for composting. If the driver observed contamination in a residential cart, he or she recorded the type of contamination and affixed an educational tag to the cart. Of the 90 single-family residential carts tagged by haulers as contaminated (0.5 percent of all residential carts), 32 percent were tagged for visible plastic contamination (State of Washington, 2017). Of the 10 commercial and multifamily carts tagged by haulers as contaminated (1 percent of all commercial/multifamily carts), 31 percent were tagged for containing plastic bags (State of Washington, 2017). Interviews of haulers indicated that participants' carts tagged one week typically are not contaminated the next week and that, on average, less than 10 percent of the participants on a residential route have contaminants in their carts. However, the haulers also acknowledged that the number of carts tagged as contaminated can be dependent on a driver's attention to detail and initiative, which supports the premise that enforcement along with proper staff training are key components of this program's efficacy (State of Washington, 2017).

In 2018, the City of Napa, California, conducted a "Flip-the-Lid" pilot audit to collect data on the types of contamination in residential organics and recycling carts (Goldstein and Coker, 2020). The city posted a message to its residents using the city's Facebook page informing them that city workers would be looking in curbside carts to visually check for items that do not belong. The audit included 1,232 homes in five neighborhoods. Staff applied stickers to carts to let residents and haulers know about contamination. Carts with greater than 20 percent contamination received an "Oops" tag and carts with greater than 40 percent contamination received an "Oops" tag and the cart was turned around so it would not be collected until the contamination was removed. Carts with less than 5 percent contamination received a "Great job" sticker. It is not clear if the pilot resulted in long-term reduction in the level of contamination in residential organics carts.

7.3. Waste Management Contract Provisions

Another strategy to prevent plastic contamination in food waste is the use of hauler contracts with well-defined expectations for contaminant reduction. These contracts encourage communication and cooperation among local jurisdictions, haulers, customers, and processors (Harrington, 2015). Examples of clearly defined actions include a requirement for the hauler to perform a visual inspection of collected material (and possibly use cart tagging) to flag accounts so the company or local government staff can follow up on the observed violations (Harrington, 2015). Contracts with processing facilities might also include provisions for the facility to flag a contaminated load, accept a contaminated load at a higher price to compensate for additional screening, or reject a load with too much contamination (Harrington, 2015). Contamination surcharge fees issued by processing facilities can deter contamination and help cover the facilities' costs to remove plastic contaminants from incoming loads (State of Washington, 2017). Facilities might also choose to reject an incoming load if it is determined to be too contaminated for processing (Harrington, 2015). The rejection of loads due to visible plastic contamination is often considered a last resort (State of Washington, 2017). Many WRRFs enter into contracts with solid waste haulers that specify the acceptable conditions of diverted organic waste for either co-digestion or composting. The efficacy of well-defined hauler contracts has not been established but, overall, they appear to be encouraged as a best practice (State of Washington, 2017).

7.4. Stakeholder Meetings

Meetings or other events can be used to educate and inform stakeholders about the effects of plastic contamination on food waste intended for processing and can lead to increased awareness of these issues (State of Washington, 2017). Examples of stakeholder groups that could be targeted with this strategy include packaging and food serviceware manufacturers, supply chain vendors, commercial end users, and municipalities. Facility tours are an effective way to show stakeholders how plastic contamination has necessitated increased investment in labor and technology (State of Washington, 2017). Understanding the investment needed to address plastic contamination can encourage stakeholder promotion, adoption, and enforcement of other approaches, such as eliminating unnecessary plastic packaging, improved labeling, education and outreach campaigns, cart tagging, and well-defined hauler contracts (State of Washington, 2017).

7.5. Food Industry Efforts

Packaging and serviceware producers and food processors can play an important role in reducing plastic contamination in food waste by finding ways to reduce the use of non-recyclable, single-use plastic packaging. Packaging producers can develop more reusable and refillable containers for food, and grocery stores can develop programs to encourage reusables and refillables. Extended Producer Responsibility[11] policies can be implemented for plastic food packaging to help shift the responsibility for contaminant removal from the food waste processing facilities to the packaging manufacturers. Producers of certified compostable food serviceware items can work toward better labeling to reduce consumer confusion about what items are compostable.

7.6. Local Ordinances

Local ordinances and bans (similar to plastic bag bans) can be implemented to prohibit the use of specific plastic items, such as non-compostable produce stickers. This approach could encourage the use of compostable stickers and upstream development of other ways to identify produce.

[11] Extended Producer Responsibility is a policy approach under which producers are given a significant responsibility (financial or otherwise) for the treatment or disposal of post-consumer products (OECD, 2021). It is used to shift responsibility for management of post-consumer products and packaging from local governments to producers.

In summary, efforts are being made by local and state governments, waste haulers, and food waste processors to reduce the level of plastic contamination in food waste collected for diversion strategies. The literature does not yet provide enough data to support a quantitative comparison of the different methods being employed. The measures of success vary across approaches and, in some cases, are not known or are still being determined. A combination of methodologies might be the most effective strategy for reducing or preventing plastic contamination and should be explored on a case-by-case basis (State of Washington, 2017; Harrington, 2015).

8. ROLE OF COMPOSTABLE PRODUCTS

A trend is emerging in the food industry to replace fossil fuel-based single-use plastic serviceware, bags, containers, and packaging with compostable materials. Compostable materials are those that degrade by biological processes to yield carbon dioxide, water, inorganic compounds, and biomass at a rate consistent with biodegradation of natural waste and that leave no visually distinguishable remnants or unacceptable levels of toxic residue (Mistry et al., 2018). This section explores how increased use of compostable packaging may impact plastic contamination in food waste streams and finished compost and digestate.

Compostable plastics are often perceived to have lower negative environmental impacts when compared with conventional plastics, and some stakeholders, including the Foodservice Packaging Institute and the Biodegradable Products Institute, have suggested that the use of compostable products can increase the overall recovery and processing of food waste. This effect is referred to as the "carrier benefit," and the use of compostable products in place of conventional plastics has found support among some seeking to increase the amount of food waste that is captured and processed (Rosengren, 2019; FPI and BPI, 2018; Kern et al., 2018). For example, when only compostable products are used in a food waste stream, waste generators are not tasked with removing food from its packaging or separating these plastic materials from the food waste before it is collected for processing (ReFED, 2016). Thus, more food waste is likely to be collected for processing than for disposal at a landfill or incinerator (ReFED, 2016). Research on the potential "carrier effect" is ongoing. An analysis conducted by Oregon's Department of Environmental Quality found that limited data do not substantiate this evidence, however, and concluded that more research is needed to fully ascertain the benefits of co-collection of compostable food serviceware and food waste (Mistry et al., 2018).

Two factors related to plastic contamination can impact the environmental benefits of compostable plastics by acting as a barrier to the compostable materials being composted (and thus fully realizing their potential environmental benefits). These factors – whether the materials reach a composter with capabilities to compost them, and whether screening for and removal of non-compostable plastics results in the removal and landfilling of compostable plastics as well – are discussed in more detail later in this section.

8.1. Sources of Compostable Plastics in Food Waste Streams

Like conventional plastic, compostable plastic has a variety of uses in the food industry. Its primary use is to replace single-use conventional plastic products, such as food packaging and serviceware (Mistry et al., 2018). Compostable plastics are also used to manufacture bags for kitchen food scraps and organics collection carts (Goldstein, 2020). Often non-compostable and compostable versions of a similar product may look similar and not be easily distinguished from one another without close inspection by consumers or processing facilities.

One important difference between compostable and conventional plastic products is that products categorized as compostable must meet specific biodegradability standards. The U.S. Composting Council advises that all compostable products should be certified as conforming to ASTM standards (D6400 or D6868) or other international standards to prevent greenwashing[12], and to ensure that the products do not create problems for compost facility operators or the environment (USCC, 2020a). These requirements are in various local and state laws as well (e.g., (State of Washington, 2020)). Meeting the ASTM standards requires individual ingredients be tested for biodegradability (consumed by microorganism) and for the product to disintegrate (physically break down during composting), and that they be tested for plant toxicity and heavy metals (USCC, 2020a). The Biodegradable Products Institute provides this certification in the United States and recently developed new guidelines for the labeling and identification of compostable products (BPI, 2020).

Compostable food serviceware and packaging can be made of bioplastics and biobased plastics, or other materials, such as paper, bamboo, and plant fibers (e.g., bagasse, a by-product of sugar cane fiber); however, the rest of this section will focus on the impacts of products made from compostable plastics. It is important to note that not all bioplastics and biobased plastics are compostable. Two types have been developed: bioplastics,

[12] Greenwashing is deceptive marketing, advertising, or public relations intended to overstate or inaccurately portray products, objectives, or policies as environmentally friendly.

which are made using biopolymers found in nature (e.g., starch, cellulose, lignin) and are biodegradable under most general conditions; and the synthetic biobased plastics, which are manmade polymers derived from monomers that originate from biological systems (e.g., polylactic acid [PLA], poly(butylene succinate)[PBS], bio-polyethylene [bio-PE]) (Polman et al., 2021). The synthetic biobased plastics are not always biodegradable and compostable (Polman et al., 2021).

8.2. Levels of Compostable Plastics in Food Waste Streams

Data on the levels of compostable plastics in food waste streams is not available. U.S. EPA estimates that in 2018, 35.7 million tons of conventional plastic was in the U.S. municipal waste stream and that 14.5 million tons of this plastic was from products categorized as containers and packaging (U.S. EPA, 2020b, 2019b). Similar estimates for compostable plastics are not available. Approximately 2.11 million tons of compostable plastics were manufactured globally in 2019, and global production capacity is set to increase to approximately 2.43 million tons in 2024 (European Bioplastics, 2020). It is not clear how much of this global total is manufactured and/or used in the United States.

The use of compostable materials is most prevalent among hospitality (including quick-serve restaurant settings) and institutional sources that frequently use single-use items, because unsorted waste has long made collection and processing of food waste impractical for these sources (Fieschi and Pretato, 2018; ReFED, 2016). Like conventional plastics, food waste and compostable plastic materials are often mixed at these locations because discarded food waste often includes food packaging and serviceware (State of Washington, 2017). In contrast, retail grocers have not widely adopted the use of compostable materials because of concerns that the use of compostable food packaging products result in a shortened product shelf life compared with conventional plastic food packaging (ReFED, 2016).

8.3. Impact of Compostable Plastics on Food Waste Recycling

Food waste mixed with compostable plastics can present operational challenges at processing facilities not originally designed to accept materials made of compostable plastics. Some composting and anaerobic digestion facilities are unable even to accept food waste mixed with certified compostable plastics because they lack the processes needed to break down compostable materials (Cooper, 2019; McDonald, 2019; Coker, 2016). Others choose not to accept certified compostable plastics due to challenges such as the time and conditions required for biodegradation.

A major concern for commercial composting facilities is whether the compostable materials they accept will compost in an appropriate timeframe because these materials require longer processing times to allow the products to fully break down than food and green clippings (Goldstein, 2020; SPC, 2017; ReFED, 2016; CORC, 2011). The inclusion of compostable plastics can impede commercial composting operations due to inconsistent rates of decomposition among the products (Geueke et al., 2018; Kern et al., 2018; Weithmann et al., 2018; CORC, 2011). Acceptance of these materials varies among facilities and localities (Rogue Disposal, 2019; Rosengren, 2019).

Compostable plastics designed to biodegrade in specific composting environments (e.g., temperatures and times) need to be delivered to composting facilities with compatible conditions that can meet biodegradability standards (Pratt et al., 2020). Not all certified compostable packaging fully composts in all facilities due to variability in the technologies and processes used at each facility, which may burden facility operators with higher costs and finished compost products contaminated with pieces of uncomposted waste (McDonald, 2019; Brinton et al., 2018; Mistry et al., 2018; Arsova, 2010). For example, few products made of compostable plastic will fully physically or biologically degrade in composting facilities that use a method that includes short active-phase retention times and little or no stabilization or maturation period (McDonald, 2019). For this reason, California has now defined compostable plastics to mean not only that the materials meet applicable ASTM standards, but also that the materials (1) demonstrate 90 percent biodegradation within 60 days; and (2) are accepted by 50 percent of collection programs and compost facilities statewide (California SB 1335).

Many composting facilities that report successful processing of compostable materials incorporate pre-grinding methods and provide additional processing time to maintain the quality of the finished compost (FPI and BPI, 2018; Goldstein, 2016). Effective biodegradation is reliant on the moisture, temperature, airflow, and microbial activity of the pile (King et al., 2015). These conditions can vary by location (and even within the pile) over the course of the composting process. Thus, for effective composting of food waste mixed with compostable materials, the facilities need to understand the composition of the waste stream and appropriately manage the composting process to maintain proper conditions (e.g., moisture, temperature).

A 5-week study was conducted in Maine and California to assess the effect of climate on the biodegradation of compostable bags present in a compost pile. Similar amounts of collected food, compost feedstock recipes, and composting processes were used; however, moisture levels differed due to the different climates of the two states (King et al., 2015). At the end of week 4, food scraps and compostable bags were approximately 90 to 95 percent degraded at the California site and roughly 85 percent degraded at the Maine site where wet, anaerobic pockets containing whole food were still noticeable (King et al., 2015). An evaluation of the biodegradation behavior of compostable plastic bags at four different anaerobic digestion (the type of facility [e.g., wet or dry] was unreported) and composting facilities in Germany concluded that the compostable bags in all four facilities were completely degraded within the standard process time of each facility. The processing times at the two composting facilities were 9.5 and 10 weeks, respectively, whereas the processing times at the two anaerobic digestion facilities were 5 and 7 weeks (Kern et al., 2018).

Difficulty in detecting the difference between compostable and conventional plastics raises operational concerns for composters and anaerobic digesters and may prevent composting of the compostable plastics. Accepting compostable plastics may increase the level of conventional plastic contamination in finished compost, degrade the value of the compost, and limit the sale of the compost in certain markets.

The presence of both compostable and conventional plastics (which may look like compostable plastics) requires haulers and processing facilities to be aware of these products in food waste streams and to possess the ability to distinguish between these materials (Sherman, 2019). Like conventional plastics mixed with food waste collected for processing, compostable plastics designed to be composted need to be segregated for processing and sent to facilities with the correct measures in place to process these materials (CORC, 2011).

When programs accept compostable products, non-compostable look-alike items also end up in composting facilities causing operating costs to increase and degrading the quality of the finished compost (Oregon DEQ, 2019). Processors may unnecessarily remove compostable products while removing conventional plastic contaminants, due to inability to detect the difference. For example, de-packaging technology at composting facilities sometimes sort out compostable materials for off-site disposal at a landfill (Cooper, 2019). Other facilities view any food packaging as a contaminant, including certified and compliant compostable plastics, and do not accept incoming material with high levels of conventional or compostable plastics to avoid issues with pre-processing plastic removal and to prevent the operational issues discussed in Section 3 (McDonald, 2019; Coker, 2016).

Due to these factors, not all composting facilities accept compostable plastics. The number of U.S. facilities that accept materials made with compostable plastic is uncertain because available sources report different values (Goldstein, 2019; Rosengren, 2019; SPC, 2017). A report from the Sustainable Packaging Coalition (an industry group) states that “a minority” of composting facilities accept compostable packaging (specific number not provided) (SPC, 2017). A survey conducted by BioCycle in 2018 identified a total of 185 full-scale food waste composting facilities in the United States. When facility operators were asked about what types of feedstocks they accept, 56 percent (53 of 95 responding facilities) reported they have permits that allow acceptance of Biodegradable Products Institute-certified bioplastics, and approximately 48 percent (an estimated 49 of 103 responding facilities) accept compostable plastic products in practice (Goldstein, 2019; SPC, 2017). A 2017 BioCycle survey of residential food waste collection programs across the county found that a little less than half of the programs (62 out of 125 programs responding) were accepting any compostable plastic products, such as compostable plastic bags, compostable plastic-coated paper products, and compostable packaging and food service items (Streeter and Platt, 2017).

Several large compost facility operators in Oregon endorsed a document stating that they do not want "compostable" packaging or serviceware delivered to their facilities for several reasons, including that those items do not always fully break down, it introduces contamination, and hurts re-sale quality (Oregon DEQ, 2019).

Anaerobic digestion facilities typically are not designed to process and break down compostable packaging and serviceware (Cooper, 2019). The bacteria present during anaerobic digestion consume some biopolymers for energy and generate biogas as a by-product, and certified compostable products may or may not be compatible with anaerobic digestion process (McDonald, 2019). Moreover, de-packagers and other pre-processing systems at these facilities might screen out compostable items before they are processed further and incorporated into the finished material (Rosengren, 2019).

In addition, new research suggests that different types of compostable plastics may vary in their methane production potential and time required for degradation in conventional anaerobic digesters. For example, PHA materials showed high methane production rates within 10 days, whereas starch-based bioplastics and PLA materials demonstrated low methane yields and remained undegraded after 250 days (Battista et al., 2021).

8.4. Effect of Compostable Plastics on the Value and Use of Finished Products

Some compost facility operators have expressed concern that accepting compostable food packaging and serviceware affects the quality and value of end products produced at their facilities (Oregon DEQ, 2019). Certification and testing programs are available to help treatment facilities determine whether compostable products will break down at their particular facility (BPI, 2019).

Current U.S. regulatory policies governing organic agriculture limit the processing of compostable materials with food waste streams to produce certified organic products. The USDA's National Organic Program (NOP) rule currently prohibits the use of compost generated with compostable plastics in certified organic agriculture (USDA, 2020).

Given the current status of the USDA's NOP rule, compost manufacturers that want to serve the certified organic market are encouraged to separate incoming material into organic approved and unapproved systems, which increases operating expenses (USCC, 2019). If compostable plastics cannot be separated from the feedstock, the facilities cannot sell compost to organic farmers, which is a concern in markets with a growing certified organic agriculture practice such as in California. The NOP has provided guidance stating compostable plates, cups, cutlery, and plastic bags represent synthetic materials that would need review and recommendation by the National Organics Standard Board before they can be utilized in compost for organic production (NOP, 2011).

9. CONCLUSIONS AND RESEARCH GAPS

This issue paper summarizes the available information regarding plastic contamination in food waste streams and the composts or digestates derived from food waste. Conclusions based on the available information are presented in Section 9.1. Given the paucity of data in several areas covered in this paper, Section 9.2 identifies research gaps that could be addressed in future research efforts.

9.1. Conclusions

Overall, this paper demonstrates that plastic contamination in food waste streams is a complex problem and one that needs further study. Microplastics have become nearly ubiquitous in the environment and are frequently detected in agricultural soils, drinking water, and aquaculture products (Zurier and Goddard, 2021). They have also been detected in pristine locations (e.g., remote arctic areas), signaling that their introduction to the environment comes from a broad range of sources that extend far beyond plastic contaminated food waste (Zurier et al., 2021).

While marine pollution has been well-established as a source of the spread of microplastics, freshwater runoff and the discharge of treated wastewater effluent (which impacts both fresh and marine waterbodies and groundwater systems) have also been identified as important sources of microplastics in the environment (Zurier and Goddard, 2021; Michielssen et al., 2016; Jambeck et al., 2015). Wastewater treatment plants, many of which were not designed to remove small particles like microplastics, also produce sludge and biosolids, which are sold and applied as fertilizers and soil amendments and likely contain microplastic particles. As the reuse of treated wastewater effluent for agricultural irrigation increases, so might the spread of microplastics to the soil and terrestrial environments (Zurier and Goddard, 2021).

Nonetheless, plastic contamination in food waste presents challenges for a broad range of stakeholders, including but not limited to those involved in waste management and processing facilities, and those who purchase and intend to use compost and digestate as soil amendments. Many key players contribute to the plastic contamination found in food waste streams, including packaging and food serviceware manufacturers, food processors, consumers, businesses, and institutions, and all of them can be a part of the solution.

Plastic contamination may be a substantial barrier to increasing the amount of food waste composted or anaerobically digested rather than landfilled in coming years. To achieve the environmental benefits of diverting food waste from landfills on a large scale, EPA must better understand the potential risks to human health and the environment of applying plastic-contaminated compost or digestate products to land, the magnitude of these risks, the most effective strategies to prevent or mitigate this risk and communicate these findings to affected stakeholders.

Further, more detailed conclusions are listed below:

- The primary source of plastic contamination in food waste streams collected for processing at compost and anaerobic digestion facilities appears to be food packaging and containers, most likely from residential, commercial, and institutional sources. Food itself is also a source of microplastic particles.

- The level of plastic contamination present in food waste streams collected for processing at compost and anaerobic digestion facilities is not well characterized in the scientific literature. Preliminary analysis by Golwala et al. (2021) found approximately 300,000 pieces of microplastics per kg of food waste collected from grocery stores in the United States (unpublished data). In addition, limited data from Washington State and Oregon reports plastic contamination rates up to 2.8 percent (by weight) in waste streams including food waste and destined for composting or anaerobic digestion. The limited data from waste composition studies and qualitative surveys of facility operators indicate that plastic contamination is higher in food waste streams than in yard debris.

- The level of plastic contamination caused by application of compost and digestate products made from food waste and used as soil amendments is unknown in the United States; however, plastics have been repeatedly observed in finished products, and facility operators have noted in qualitative surveys that maintaining product quality in light of the plastic contamination is a problem. Limited quantitative data are available. In European studies, microplastics were identified in finished materials.

- Processing facilities sometimes prohibit food waste streams or reject incoming food waste streams collected for processing at compost and anaerobic digestion facilities due to plastic contamination levels, thus reducing the amount of food waste diverted from landfills.

- Plastic contamination may reduce the environmental and economic benefits of composting and anaerobic digestion of food waste. For example, an initial study indicated plastic contamination may impede the production of methane from food waste during anaerobic digestion, and another study found the presence of microplastics can alter greenhouse gas and ammonia emission levels during composting.

- The use of pre-processing approaches and contaminant-removal technologies at compost and anaerobic digestion facilities can reduce the amount of plastic contamination in food waste streams but are not fully effective. Efficiencies associated with each removal technology are not well reported in the literature. Further, it is unclear to what extent these technologies (e.g., shredders, grinders and de-packagers) may inadvertently introduce microplastics or nanoplastics into the end products.

- Techniques to prevent plastic contamination in food waste streams, such as education and outreach, cart tagging programs, and hauler contract provisions are being used in some jurisdictions. Limited data on prevention programs shows mixed results. If successful, prevention could reduce the complexity and increase the desirability of processing food waste streams.

- Much remains uncharacterized about the environmental fate of and exposure to plastic particles in composts and digestates generated from food waste and used as soil amendments, making it challenging to evaluate risks to human health and the environment. The available literature does not provide substantial evidence of environmental or human health effects that are occurring as a result of plastic contamination in finished compost and digestate products produced using food waste streams. It is also unclear how the risks associated with these products generated from food waste compare to those of background levels of plastic contamination and other sources of plastic contamination in the environment, such as other soil amendments (synthetic or made from wastewater sludge and biosolids).

- There are questions and concerns regarding the release of microplastics and nanoplastics into the environment as a consequence of the grinding, shredding, or de-packaging that occurs at processing facilities and the breakdown of larger plastic fragments in the soil over time.

- Regardless of risks to human health and the environment, the presence of visible plastic particles in finished products reduces their value and marketability.

- Owing in part to the uncertainty about environmental exposures and risks, regulations and standards implemented to reduce the amount of plastic present in composts and digestates generated from food waste and used as soil amendments vary by location. In the United States the federal government does not regulate plastic contamination in finished products applied to land; however, some U.S. states and international governments do. These limits vary in both the allowable levels of contamination and fragment size thresholds. European standards generally address smaller fragment size thresholds than U.S. state regulations. Overall, the regulations in the United States typically do not address plastic fragments less than 4 mm, and regulations identified for other countries do not address sizes smaller than 1 mm. Limits may be set based upon detection levels, which vary along with the cost and level of complexity of available testing methods, and aesthetic concerns (e.g., preventing visible plastics) given that exposure and risk analysis is not available. Plastic contamination in finished digestate or compost tends to be heterogenous, presenting challenges for collecting representative samples. Measurements from small samples are not indicative of the overall conditions of the finished product.

- Compostable plastics present a unique set of operational challenges to both consumers and facilities seeking to compost these products when mixed with food waste. Compostable plastic materials can look similar to those made with conventional plastics, leading to contamination of the compostable food waste stream with conventional plastics, and to the removal of the compostable plastics along with conventional plastics during screening and de-packaging at processing facilities, eliminating the potential environmental benefit of compostable materials.

9.2. Research Gaps

Plastic contamination in food waste streams and its implications for food waste management, as well as human health and the environment, is an emerging issue in the early stages of investigation. Scientifically rigorous data are needed to address several important research gaps.

Priority Research Needs:

1) **Research to discover the level of plastic contamination and associated particle sizes (e.g., microplastics or nanoplastics) in finished composts and digestates generated from food waste and used as soil amendments in the United States.** This data is imperative to determining the magnitude of the potential problem and calculating the potential risks to human health and the environment from land application of compost and digestate made from food waste. This data should be compared to background levels in the soil and to contamination levels in land-applied biosolids. Additional sampling and quantification methods might be needed to accurately measure levels of nanoplastics in compost, digestate, and soil.

2) **Research to ascertain the contribution of food waste to plastic contamination in compost and digestate used as soil amendments.** Typically, food waste is mixed with other organic waste streams, such as yard debris, before composting or anaerobic digestion begins. Research is needed to determine the levels and particle sizes (e.g., microplastics or nanoplastics) of plastic contamination in food waste streams and the mixed waste streams (which include food waste) that serve as final feedstock for composting and anaerobic digestion in the United States. This data would allow us to understand the relative contribution of food waste and target solutions.

3) **Research to determine the impacts of technologies (e.g., shredders, grinders and de-packagers) commonly used by processors on the level of plastic contamination and size of plastic particles.** The efficiency at which the available de-packaging technologies remove plastic contaminants is not well reported in the literature. Data are needed to better understand how effective these technologies are at removing plastic contamination present in food waste and their impact on the size of particles that remain in the waste stream. The impacts of grinders and shredders on final particle size should also be evaluated.

4) **Research to determine the effect of microplastic contamination on greenhouse gas and ammonia emissions levels during composting and methane yield from anaerobic digestion.** Results of initial studies by Sun et al. (2020), Lim et al. (2018), and Wei et al. (2019) need to be confirmed through additional research and plastic types commonly found in food waste streams need to be tested.

5) **Research to identify the most effective strategies to prevent plastic contamination in food waste streams.** Although evidence on the use of strategies, such as education and outreach, cart tagging programs, hauler contract provisions, stakeholder meetings and events, and upstream strategies, such as improved labeling, compostable products, and local ordinances, to reduce the amount of plastic collected in food waste streams was found, the outcomes of these efforts have not been well documented. The efficacy of these approaches is unclear. Stakeholders who implement prevention programs should be encouraged to report on the observed degree of reduction in plastic contamination, even if results do not

indicate the program has been successful. More information on the successes and lessons learned from these efforts would be useful for informing future initiatives.

6) **Research to assess exposure and the potential risks to human health and the environment from land application of plastic-contaminated compost and digestates.** More research is needed on the fate and persistence of plastic particles in environmental media after the use and application of soil amendments made from compost or digestate generated from food waste in order to assess exposure. Comparison of these findings to similar research on plastic present in the environment introduced from other sources is needed to improve our understanding of the relative risk associated with plastics from food waste. Additional comparison between the levels of microplastic in finished products and levels of microplastic in background soils would also provide important information for risk assessment. In addition, more research is needed on the specific health and environmental effects of plastic particles in the environment (e.g., impacts on soil conditions and plant growth) in typical use scenarios (e.g., land application to soil).

Additional Research Needs:

- Research to characterize the plastic contamination in food waste streams, including the types of plastic items (e.g., food packaging, stickers, bags) found and the sectors from which it is collected (e.g., residential, commercial and institutional). This data would help stakeholders tailor successful prevention and mitigation strategies.

- Research to determine the impact of plastic contamination on the diversion of food waste from landfills. Composting and anaerobic digestion are important processes that could dramatically reduce the amount of landfilled organic waste and associated methane emissions. Furthermore, soil amendments generated from food waste have many beneficial effects on soil and plant growth. While available information indicates that some food waste is sent to landfills or combustion facilities rather than processed due to the presence of plastic contamination, the amount of plastic present in food waste that warrants rejection by processing facilities is not reported in the available literature, nor is the frequency for which incoming material is rejected by these facilities. In addition, although the visible presence of plastic is clearly a cause for concern among those who use products made from food waste, quantitative estimates of the extent to which plastic contamination affects the marketability or quality designations (e.g., organic) of finished products or prevents these products from being used more broadly is not reported in the literature at this time. Information could be obtained through surveying facility operators and reviewing contracts between processing facilities and local authorities, haulers, and waste contributors. This data would allow for better understanding of the impact of plastic contamination on the amount of food waste processed in lieu of landfilling or combustion in the United States.

- Research to measure the potential “carrier benefit” of compostable plastics and the effect of using compostable plastics on plastic contamination in food waste streams. More research is needed to understand the potential carrier benefit (i.e., the idea that the use of compostable products can increase the overall capture and processing of food waste) of compostable food serviceware. Studies should assess rates of food waste recovery with and without the use of compostable serviceware, as well as rates of contamination in the associated food waste streams and confusion among consumers associated with the mixing of these materials with food waste. Research comparing per capita food waste collected in programs that accept compostable products with those that do not (e.g., Seattle and Portland) would provide useful information to assess the benefits of compostable products. This information would allow us to understand the relationship between plastic contamination and the use of compostable plastics, as well as provide data that could be used in broader analyses of the life cycle environmental value of compostable plastics.

Additional investigation into the research needs and data gaps presented above will improve the understanding of the levels and sources of plastic contamination, and its impacts on food waste collection and processing, human health, and the environment. This information will allow U.S. federal, state, and local policymakers to develop evidence-based strategies to increase the demand for food waste as a feedstock for composting and anaerobic digestion, improve the quality and value of finished products generated from food waste, and limit potential harm to human health and the environment. Ultimately, further research in this area will contribute to a more environmentally sustainable management of food waste in the United States.

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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 (Part 1) and associated issue papers, including this paper on plastic contamination in food waste streams. The objective of this 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 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 source, as well as the key gray literature (see Section A.2.) 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.

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 Grey 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). 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) were used for grey literature. screeners applied the tags in columns within Excel.

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