United States Department of Agriculture
Agricultural Marketing Service | National Organic Program
Document Cover Sheet
https://www.ams.usda.gov/rules-regulations/organic/petitioned-substances

Document Type:

☐ **National List Petition or Petition Update**

A petition is a request to amend the USDA National Organic Program's National List of Allowed and Prohibited Substances (National List).

Any person may submit a petition to have a substance evaluated by the National Organic Standards Board (7 CFR 205.607(a)).

Guidelines for submitting a petition are available in the NOP Handbook as NOP 3011, National List Petition Guidelines.

Petitions are posted for the public on the NOP website for Petitioned Substances.

☒ **Technical Report**

A technical report is developed in response to a petition to amend the National List. Reports are also developed to assist in the review of substances that are already on the National List.

Technical reports are completed by third-party contractors and are available to the public on the NOP website for Petitioned Substances.

Contractor names and dates completed are available in the report.

Compostable Materials (Compostables)

Crops

Summary of Petitioned Use

This limited scope technical report provides information to the National Organic Standards Board (NOSB) to support the review of compost feedstocks beyond those identified as "plant and animal materials" in the National Organic Program (NOP) regulations.

The National Organic Program received a petition for rulemaking in August 2023, that requests multiple amendments to the organic regulations (Biodegradable Products Institute (BPI), 2023). They explicitly request that the term "plant and animal materials" be removed from the regulations and replaced with "compost feedstocks." They further request that the term "compost feedstocks" be defined in the regulations to include plant and animal materials as well as any other material that meets relevant ASTM standards for biodegradability and compostability. The petitioner's rationale for these proposals largely pivots on the growth of the market for bioplastic packaging and emerging state laws mandating limits on the use of single-use plastics. They also assert that disallowing packaging materials currently permitted for direct food-contact as compost feedstocks is "nonsensical." Furthermore, the petition contends that including each allowed compostable material on the *National List of Allowed and Prohibited Substances* is unnecessary given the precedent that synthetic additives in paper products are not individually listed despite paper itself being permitted as a compost feedstock. Finally, the petitioner requests the adoption of the "*de minimis*" doctrine in the regulations in reference to compost feedstocks that do not directly appear on the National List. Under the *de minimis* paradigm, the program would permit trace quantities of uncomposted non-National List substances, akin to the allowance of trace pesticide residues on green waste.

The NOSB solicited written public comments and heard oral public comments at the Spring 2024 and Fall 2024 meetings. Subsequently, the NOSB requested that this technical report focus on several key concepts related to the compostability of biopolymer and cellulosic fiber-based food packaging substances (NOSB, 2024a, 2024b, 2024c). In support of that request, we explore the characteristics, compositions, and breakdown products of a wide range of synthetic food packaging plastics in this report. To a limited degree, we also discuss cellulosic fiber-based materials, including biopolymers and paper (and composites of the two), as well as their coatings, additives, and performance-enhancing components.

Background

<u>What are "compostables?"</u>

For compostable food packaging, general definitions are elusive.[1] This group of materials includes a wide variety of products that are not identified entirely by composition or formulation. The commonality among these products is that they are marketed and sold according to an intended end of life process—that is, they are intended to be composted.

Although many types of products can be composted, this report focuses on compostable packaging that comes into contact with food: primarily synthetic food packaging plastics and cellulosic fiber-based materials. We refer to these materials as "compostables" throughout this report.

Compostables can include the following items (Composting Consortium & BPI, 2023; Goldstein & Coker, 2021; Purkiss et al., 2022):

- takeout boxes and clamshells
- cutlery
- cups and lids
- bowls
- straws
- plates and trays
- pre-sealed prepared food packages such as tubes and pouches[2]
- bags and films
- coffee pods

[1] Authors of literature that we consulted for this report use inconsistent definitions for compostable materials. Where possible, we have summarized the work of authors in this report using consistent terminology. Our discussions of materials and categories take this into account as much as possible, defining terms and parsing statements to prioritize clarity and accuracy.

[2] Conventional petroleum-based flexible and semi-flexible plastic items are especially difficult to recycle (Allison et al., 2021), compostable and degradable versions are more popular and economically viable.

The materials they are composed of may have the *appearance* of plastic, paper, cardboard, foam, or combinations thereof (Composting Consortium & BPI, 2023). We say they have the appearance of these materials because in reality, they may be composites of different layers or components and include waxes, additives, coatings, or covers. Most packaging that is capable of being composted is not readily identifiable unless marked: it may be clear or opaque and any color. Product formulations are proprietary (some representing the latest technology), and not publicly available. However, labeling standards and conventions are emerging, leading manufacturers to create more visually distinct products by using green, brown, or off-white packaging color, color accents such as a green stripe, and distinguishing communication such as printed or embossed words and certification seals, to aid proper disposal (Composting Consortium & BPI, 2023; Goldstein & Coker, 2021) Packaging manufacturers have begun to include end-of-life considerations in product design, but best practices and standard solutions are still far from coalescing. Third party organizations including BPI, the Compost Manufacturing Alliance, NSF (formerly the National Sanitation Foundation), and TÜV Austria offer voluntary certification programs for compostable products. ASTM International (formerly the American Society for Testing and Materials) and ISO (the International Organization for Standardization) maintain the standards to which these programs certify compliance in North America.

<u>How are compostables regulated?</u>

The organic standards describe specific management practices to successfully produce compliant compost from plant and animal materials for organic production, including requirements for carbon-to-nitrogen ratios, temperature over time, and minimum mixing or turning [7 CFR 205.203(c)(2)]. The regulations allow natural substances as compost feedstocks, unless prohibited in § 205.602. *NOP 5021: Guidance, Compost and Vermicompost in Organic Crop Production* clarifies that additional compost (and vermicompost) practices are allowed in organic production, providing flexibility for variation in feedstocks and site-specific management practices (NOP, 2011). These alternative compost methods are also cited in *NOP 5034-1: Materials for Crop Production* (NOP, 2016). Only one class of synthetic substances are allowed as a compost feedstock: newspaper or other recycled paper without glossy or colored ink. Although many compostable products include plant materials, they also contain a wide variety of synthetic substances (Food Standards Agency, 2023). According to the organic standards, organic producers must not use "any fertilizer or composted plant and animal material that contains a synthetic substance not included on the National List" [§ 205.203(e)(1)].[3]

States, municipalities, and waste management districts are taking actions that involve compostables, with goals including the following (Babka, 2019; Goldstein & Coker, 2021; Vermont DEC, 2024):

- diverting food waste from landfills
- recovering resources and energy
- reducing plastic pollution
- conserving soil
- reducing greenhouse gas (GHG) emissions

Jurisdictions are imposing bans on the sale of bags and other single use plastics, and some explicitly consider compostables to be acceptable alternatives (Goldstein & Coker, 2021). Twelve states ban or restrict food from landfills (ReFED, 2025) Some residents are required to separate food scraps from garbage (Phillips, 2024). Compostables may be considered food scraps or garbage, depending on the local collection service. Eleven states enacted new measures in 2024 to reduce plastic packaging, including allowing restaurants to pack ready-made food in consumer-owned containers (Phillips, 2024). Many measures include funding for developing infrastructure to process the diverted food waste. In addition, states are regulating labeling and packaging of compostables to reduce

[3] At time of writing of this report, NOSB is considering changes to the details that define allowable compost. And stakeholders have petitioned for additional revisions (see *Focus Question #2*).

confusion among consumers and waste managers. Many are banning confusing phrases such as "biodegradable" or "made from plants" (see examples in *Table 1*, below):

Table 1: Regulations on compostables and waste management in selected jurisdictions.

Jurisdiction	Requirements
Austin, Texas	Under the Universal Recycling Ordinance, all multifamily properties are required to provide convenient access to commercial composting services (ReFED, 2025).

California	Residents and businesses are required to separate food scraps from garbage (Phillips, 2024). Effective January 1, 2026, state law requires that compostables meet either of the following criteria (State of California, 2018):
	• They are collected and accepted by 75% of organic waste recycling programs and compost facilities that accept mixed materials statewide.
	• They are included in a "takeback program" that annually recovers 75% of food service packaging items that are distributed at state food service facilities, such as government buildings and correctional institutions.
	Plastic and plastic-coated food packaging must meet additional criteria:
	• As applicable, meet the ASTM standards:
	  ○ D6400-19, *Standard Specification for Labeling of Plastics Designed to be Aerobically Composted in Municipal or Industrial Facilities* or
	  ○ D6868-19, *Standard Specification for Labeling of End Items that Incorporate Plastics and Polymers as Coatings or Additives with Paper and Other Substrates Designed to be Aerobically Composted in Municipal or Industrial Facilities*.
	• Demonstrate 90% biodegradation within 60 days.
	• Comply with the statutory requirements to be labeled "compostable" in California.
	A compostable plastic product meeting ASTM Standard D6400 may not be sold in California as "compostable" unless it is (or is solely composed of) "an allowable agricultural organic input under NOP requirements (State of California, 2021).

Maryland	Products labeled "compostable" must meet ASTM D6400 or ASTM D6868 standards and any applicable labeling guidelines in the FTC *Guides for the Use of Environmental Marketing Claims* (87 FR 77766, December 20, 2022). Products labeled "biodegradable," "decomposable," etc., are prohibited (Goldstein & Coker, 2021).
New York City	City residents are required to separate organic waste from trash (Phillips, 2024).
Vermont	All food scraps and "mandated recyclables" are banned from disposal in trash, statewide. Additionally, there are limitations on commercial and retail use of single-use items. Use and sale of expanded polystyrene food and beverage containers are banned (Vermont DEC, 2024).
Washington State	Organics collection is required for single-family residents in urbanized areas (USCC, 2024). Compostable packaging must meet detailed labeling standards. (Goldstein & Coker, 2021). Certain businesses generating at least 4 cubic yards of organic waste per week must subscribe to an organic waste removal service (Washington State, 2023).

What terms are used to describe the breakdown of compostables?

Composting is a complex process (see *Focus Question #3* for details). At a basic level, food packaging is compostable if (Goldstein & Coker, 2021):

- It contributes to the composting process, providing nutrients.
- It biodegrades during the composting process.
- It does not contaminate soil, air, or water.

While they are not the only ways that materials break down, disintegration and biodegradation are among the important processes that compostables undergo at their end of life. We define these and other related terms below:

> **Disintegration** is the physical process in which substances break down into smaller pieces (Wyman & Salmon, 2024). This process may include physical disintegration by light, mechanical force, water, and other environmental conditions. Compostability standards lay out how small particles must be after a given composting time (ASTM International, 2021b, 2021c, 2021d).
>
> **Biodegradation** is the breakdown of a material by organisms, especially microorganisms, where the carbon in the material is converted to carbon dioxide.
>
> **Biodegradability** is the capacity of a substance to be broken down by organisms, especially microorganisms, and its carbon converted to carbon dioxide. Biodegradability depends heavily on the environment. A common standard is reaching a threshold of at least 90 percent biodegradation in less than 6 months (ASTM International, 2021b). However, manufacturers face difficulty in ensuring appropriate degradation for a given product (Zimmermann & Geueke, 2022). Whether a product is used right away or stored affects its potential to biodegrade before or during use; and eventual planned biodegradation depends on disposal conditions (Zimmermann & Geueke, 2022).

Biodegradation is difficult to observe directly in the field without meticulously tracking, documenting, and measuring specific pieces over time. Researchers can quantify it in test conditions by measuring oxygen consumed or carbon dioxide produced, allowing them to calculate carbon consumed (Wyman & Salmon, 2024). Biodegradation is rated scientifically in categories ranging from primary to ultimate, each with specific definitions (Wyman & Salmon, 2024). However, compostability standards generally do not require ultimate biodegradation (see *Focus Question #2*).

Where are compostables composted?

The process of collecting compostables along with food waste, and subsequent composting is sometimes referred to as "organics recycling" (Purkiss et al., 2022; Van Roijen & Miller, 2022). For the most part, manufacturers intend for compostables to be processed at commercial or industrial composting facilities. "Home compostable" items that individuals or neighborhood groups can compost at lower temperatures are a smaller subset of materials. However, relatively few composting facilities accept compostables, especially plastics, due to concerns including (Babka, 2019; Phillips, 2024; Vermont DEC, 2024) (see *Focus Question #6*):

- contamination from look-alike products and microplastics
- inadequate breakdown of compostables
- worsened compost quality

How are they identified or labeled?

As described above, what qualifies as compostable packaging can vary, and consumers exhibit substantial confusion when purchasing and disposing of these items (Goldstein & Coker, 2021). Third-party certifiers maintain product lists or offer a seal or mark to distinguish certified compostable products. Although ASTM standards form the basis for these certification programs, the certifiers impose additional requirements such as PFAS contamination limits or biodegradability testing. The relevant standards are described in detail in a later section (see *Focus Question #2*).

The different terms that manufacturers use on labels and packaging are subject to varying degrees of standardization and regulation depending on their composition and where they are sold. The terms "biodegradable," "made from plants," and "bio-based" lack standard meanings and are poorly understood by the public (Babka, 2019; Composting Consortium & BPI, 2023; Ruf et al., 2022). Also, these terms may apply to only certain components of the packaging, leaving films and microplastics that persist. "Biodegradable" in marketing plastic products is prohibited by law in California, Colorado, Maryland, Minnesota, and Washington state (Goldstein & Coker, 2021). The Federal Trade Commission has published Green Guides for avoiding unfair or deceptive marketing messages based on environmental claims (87 FR 77766, December 20, 2022).

Some compostable products have been designed to resemble their conventional fossil-fuel-derived counterparts. As a result, compostable items can be difficult to differentiate from fossil products (Zimmermann & Geueke, 2022). These "look-alike" products cause more contamination during waste collection (Phillips, 2024). Jurisdictions are beginning to require accurate labeling of compostables (Babka, 2019).

Generally, what are the types of compostables?

Bio-based products have been defined in the Farm Bill since 2002: "Commercial or industrial goods (other than food or feed), composed in whole or in significant part of biological products, forestry material, or renewable domestic agricultural materials, including plant, animal or marine materials" (89 FR 4770, January 24, 2024). Although terms overlap, bio-based products do not necessarily break down during composting; some are not compostable or biodegradable (see *Figure 1*).

Bio-based compostables can contain bamboo, wood, cornstarch, wheat, corn, soy, tapioca, cassava, and sugar/bagasse, including agricultural byproducts, and seaweed (Food Standards Agency, 2023). A wide variety of additives are applied according to the type of material and function. For example, plant fibers readily absorb moisture, grease, and oils. These materials, like food-grade papers, require additives for moisture- and grease-resistance (Semple et al., 2022). Paper, cardboard, and molded fiber may have waxes or coatings that also serve as binders and fillers (Semple et al., 2022).

Molded pulp is commonly made from inedible fibrous wastes (stalks, leaves, seed pods), and can be made from recycled materials including paper. (Semple et al., 2022) In addition to grease and moisture resistance, additives may serve to provide strength in the final product, or serve a processing function, such as a foaming or bleaching agent (Semple et al., 2022).

Bioplastics come from renewable sources such as the agricultural byproducts listed above, with the help of microbes. They may contain natural polymers or fibers from starch, cellulose, or bamboo, and are often mixed with man-made synthetic polymers. Or, they may chemically resemble conventional plastics (Zimmermann & Geueke, 2022). Roughly half of all bioplastics produced are non-biodegradable (Semple et al., 2022).

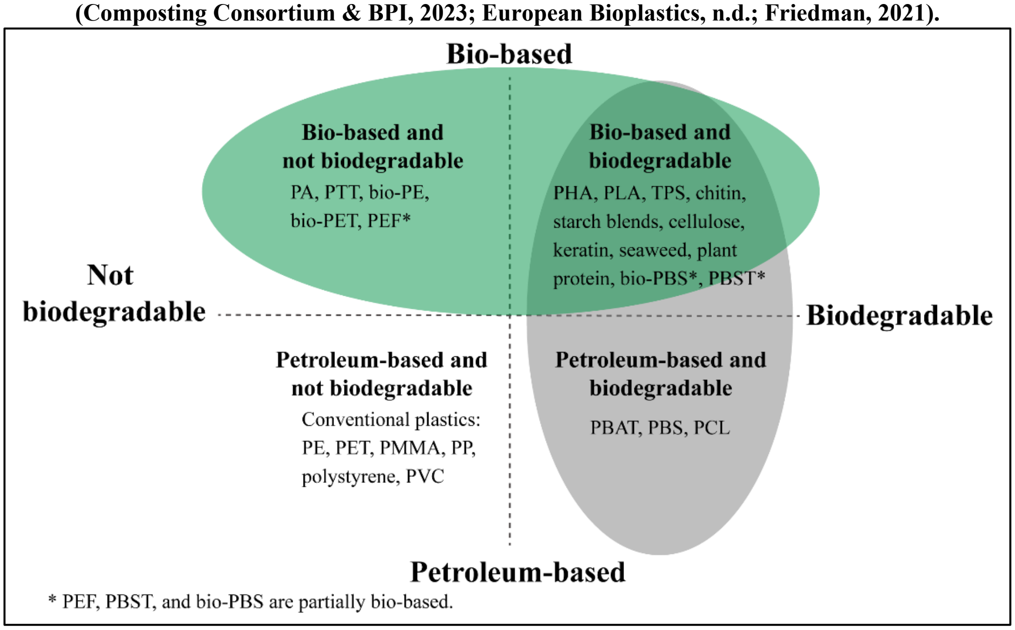
Packaging is the main use of all plastic in general, with 146 million tons used in 2015 (Babka, 2019) and nearly 360 million tons produced (packaging representing 40%) in 2018 (Allison et al., 2021). The bioplastics market is still small. It represented less than 1% of all plastic produced in 2021 worldwide, or about 2.5 million tons, mostly in the forms of PBAT, PLA, and starch blends (Zimmermann & Geueke, 2022).

The most common bioplastic materials include (Goldstein & Coker, 2021; Zimmermann & Geueke, 2022):

- polylactic acid/polylactide (PLA)
- crystallized PLA (CPLA)
- polybutylene adipate terephthalate (PBAT): biodegradable synthetic plastic with cornstarch
- polybutylene succinate (PBS)
- polyhydroxyalkanoates (PHAs)
- thermoplastic starch (TPS)
- cellulose
- chitin

Additional materials are described in the *Appendix*, *Table 8*.

Figure 1: Bio-based and biodegradable plastics[4]
(Composting Consortium & BPI, 2023; European Bioplastics, n.d.; Friedman, 2021).



To compensate for limitations inherent to bioplastic materials, such as brittleness and low gas barrier properties, bioplastics can contain additives such as synthetic polymers, fillers, and plasticizers. The specific types, amounts, and hazards of these chemicals in bioplastics are rarely disclosed (Zimmermann & Geueke, 2022). Some specific examples of additives described in literature include (Qian et al., 2025, 2025; Surendren et al., 2022):

- glycerol
- sorbitol
- polyethylene glycol (PEG)
- citric acid
- vanillin
- acetyltributylcitrate (ATBC)
- tributyl citrate (TBC)
- vegetable oils

[4] Materials not mentioned elsewhere in this report include polyamide (PA), polytrimethylene terephthalate (PTT), polyethylene terephthalate (PET), polyethylene furanoate (PEF), polymethyl methacrylate, and polybutylene succinate-co-butylene terephthalate (PBST).

Manufacturers also use colorants and antimicrobials (Jin et al., 2024). With molded fiber and bioplastic as basic constituents, manufacturers can create bioplastic mixtures, laminates, and composites. These items may not break down uniformly (Gómez & Michel, 2013; Hermann et al., 2011).

Biodegradable plastics can come from starch, cellulose, PLA, PHAs, or polyesters synthesized from a fossil source (Babka, 2019). ASTM defines these as "degradable plastic in which the degradation results from the action of naturally occurring microorganisms such as bacteria, fungi, and algae" (ASTM International, 2021b).

Many of the potential benefits that compostables offer, such as reduced plastic pollution and increased food scrap diversion, rely on consumer awareness and behavior, as well as collection and processing infrastructure. These products may facilitate the collection of food scraps, because consumers can dispose of the packaging with food waste inside (potentially further reducing GHG emissions from landfills) (Friedman, 2021; Springle et al., 2022). However, this only happens where collection services exist, and where composters accept compostables as feedstocks. As of 2023, only about 12% of American households in 25 states had access to residential food waste collection, with composting infrastructure processing up to 4% of total food waste (Goldstein et al., 2023a, 2023b). Twenty-nine percent of composting facilities do not accept compostables (Goldstein et al., 2023b).

Although transition is occurring, the vast majority of compostables are still sent to landfills or incinerators (Babka, 2019; Beyond Plastics, 2024; State of Oregon DEQ, 2018). Consumers often send compostables into recycling streams, but compostable products containing different materials are almost impossible to recycle, and some compostable materials can contaminate recycling materials, such as PET (Babka, 2019; Beyond Plastics, 2024; Raźniewska, 2022). Compostables can also become litter, especially where collection and processing infrastructure is underdeveloped, if consumers think they will break down completely in the environment. However, these materials degrade slowly outside of industrial composting conditions, and may not break down at all in marine environments (State of Oregon DEQ, 2018; UN Environment Programme, 2023). In fact, according to Van Roijen & Miller (2022), if all future production of plastics were replaced with biodegradable plastics, without changing the waste management system, the release of methane during biodegradation in landfills would raise the overall greenhouse gas emissions to surpass those from conventional plastic use.

What are per- and polyfluoroalkyl substances (PFAS), and how are they used in compostables?

Among the many additives and fillers that go into producing compostables, synthetic per- and polyfluoroalkyl substances (PFAS) provide grease- and water-resistance (Goossen et al., 2023; Phelps et al., 2024; A. S. Timshina et al., 2024). For example, PFAS is used as an additive to make single-use disposable plastics, paper, and cardboard-based and molded fiber materials (Goossen et al., 2023). PFAS have been used for over 50 years, resulting in widespread contamination (A. S. Timshina et al., 2024). These compounds can be detected worldwide in water, soil, and air and are ubiquitous in modern life (Khair Biek et al., 2024; A. S. Timshina et al., 2024).

PFAS can be an unintentional contaminant in compostables as well. Manufacturers can unknowingly use PFAS contaminated source materials (Goossen et al., 2023; Phelps et al., 2024). For instance, researchers have found PFAS in finished paper products—like toilet paper and paper plates—even when the manufacturers of those finished products did not use PFAS (Goossen et al., 2023). We address the prevalence of PFAS in compostables in *Focus Question #1*.

One complicating factor for understanding PFAS is that these substances and their breakdown products can combine with each other (or with plastics) during manufacturing or recycling, forming new compounds of unknown toxicity (Geueke, 2018; Geueke et al., 2024). These new substances are not considered part of a compostable product's composition, nor can these new substances be measured easily. In addition, some substances within packaging (intentionally added or otherwise) may migrate into the food product (Geueke, 2018).

What are the health risks associated with PFAS?

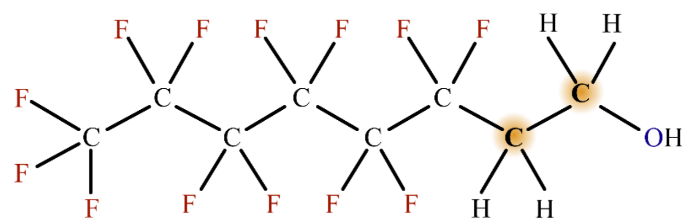
PFAS are known to pose serious health risks to humans and animals. In humans, they are known to cause different types of cancer (*e.g*., kidney and testicular cancer), thyroid disease, kidney disease, liver disease, decreased sperm quality, and immunotoxicity (Khair Biek et al., 2024; Y. Wang et al., 2023). In animals, they are known to cause reproductive and developmental toxicity, testicular cancer, and immune suppression. PFAS have biodegradation half-lives that range from days to years, in the environment (Choi et al., 2019; Schaider et al., 2017a). There is very little information regarding PFAS half-lives in humans (Schaider et al., 2017a).

What is the composition and chemical structure of PFAS?

PFAS are known as "forever chemicals" due to the strength of their carbon-to-fluoride bond (Buck et al., 2011; Choi et al., 2019; A. Timshina et al., 2021). This bond is the reason for their persistence in the environment. The bond is extremely strong and stable, requiring a significant amount of energy to begin the breakdown process (Buck et al., 2011; Y. Wang et al., 2023). Currently, the only method regularly used to completely destroy PFAS is thermal processing, which involves incineration at temperatures above 1000 °C (Winchell et al., 2021). However, many PFAS in food packaging materials partially degrade in certain environments (such as compost piles) (Dinglasan et al., 2004; Khair Biek et al., 2024; Stroski et al., 2024). Their compostability is complex and discussed in *Focus Question #1* and *Focus Question #3*. Some PFAS degrade to form derivatives (Buck et al., 2011; Munoz et al., 2022).[5] These derivatives can eventually become stable and highly persistent PFAAs.

PFAS are named according to their structure. Perfluoroalkyl substances are substances where all fluoride atoms bonded to carbon atoms replace hydrogen atoms present in the originating material (Buck et al., 2011). Polyfluoroalkyl substances are those where fluoride has replaced at least one but not all hydrogen atoms of the originating material. There is at least one perfluoroalkyl unit (C_nF_{2n+1-}) in a polyfluoroalkyl substance (Buck et al., 2011). Substances with a "*n:x*" name, such as 6:2 FTOH, describe the number of carbon atoms bonded to fluoride atoms ("*n*") and the number of carbon atoms bonded to non-fluoride atoms ("*x*"). 6:2 FTOH describes a compound with six carbon atoms bonded to fluoride atoms and two bonded to hydrogen or oxygen (*Figure 2*).

Figure 2. 6:2 FTOH chemical structure



6:2 Fluorotelomer alcohol (6:2 FTOH)

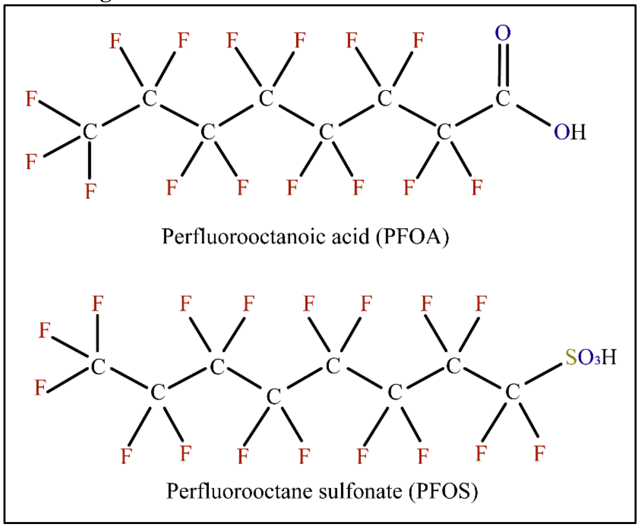
PFAS are generally described by the literature as "short-chain" or "long-chain" based on their carbon chain length (Buck et al., 2011):

- Short-chain refers to perfluoroalkyl carboxylic acids with six or fewer perfluorinated carbon atoms and perfluoroalkane sulfonates with five or fewer perfluorinated carbon atoms.
- Long-chain refers to perfluoroalkyl carboxylic acids with seven or more perfluorinated carbon atoms and perfluoroalkane sulfonates with six or more perfluorinated carbon atoms.
- Ultra-long chain PFAS, defined as those with carbon chains exceeding nineteen carbon atoms. However, researchers do not know how prevalent ultra-long chain PFAS are (Stroski et al., 2024).

Long-chain PFAS are the most studied because they bioaccumulate more often than short-chain compounds (Buck et al., 2011). These include perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS), both comprising an eight-carbon chain (*Figure 3*). PFAS are comprised of a fluoroalkyl tail (C_xF_y) and one or more hydrophilic (polar, "water-loving") functional groups (*e.g.,* carboxylate, sulfonate, hydroxy, quaternary ammonium, and betaine) (Barhoumi et al., 2022). The overall electric charge of these functional groups is different from the electric charge of the fluoroalkyl tail to varying extents, which influences how PFAS interact with other substances. A large difference in charge can lead to the partition effect, where one end of a PFAS interacts in the opposite way as the other end (*i.e.,* one end is attracted to a substrate while the other half is repelled) (Barhoumi et al., 2022). The partition effect is not observed in all PFAS and is highly dependent on the environment where the interaction takes place. We discuss the partitioning effect and environmental factors in *Focus Question #1*.

[5] PFAS are primarily manufactured in two ways: electrochemical fluorination and telomerization. Electrochemical fluorination uses a C-H base material and reacts with anhydrous hydrofluoric acid. All hydrogen atoms in the chain are replaced by fluorine via electrolysis. The process produces a mixture of linear and branched isomers (compounds with the same molecular formula but different special arrangements). PFOS, PFOA, and their derivatives are manufactured through electrochemical fluorination.
Telomerization involves a reaction of a perfluoroalkyl iodide (known as the "telogen") with tetrafluoroethylene, producing longer perfluorinated chains known as perfluoroalkyl iodides (Telomer A). Telomer A may again react with ethylene, yielding a longer carbon chain compound (Telomer B). Telomer B is an intermediate that produces additional building blocks that are further reacted. "Fluorotelomer-based" surfactants and polymers are the result of these reaction sequences. Telomerization produces primarily or exclusively linear PFAS.

Figure 3. PFOA and PFOS chemical structures



Other notable types of PFAS are fluorotelomer alcohols (FTOHs) and perfluoroalkyl acids (PFAAs) ([*Table 2*](#)). FTOHs are typically used as precursors in the production of fluorinated polymers used in paper, wax, adhesive, metal, and paint products and as substitutes for PFOS (Dinglasan et al., 2004). PFAAs are often described as "terminal PFAS" because they are not likely to degrade further under typical environmental conditions (Choi et al., 2019; A. S. Timshina et al., 2024). PFAAs can be short- or long-chain and made through the degradation of less stable substances or formed by precursor substances (Buck et al., 2011).

Many PFAS have been phased out in the United States (see [*What is the history of PFAS in food contact materials?*](#)). Manufacturers may choose to use homologs of phased-out compounds (Choi et al., 2019; Schaider et al., 2017a).[6] For example, PFHxA is a six-carbon homolog of eight-carbon PFOA (phased out) and shows some of the same adverse human toxicity effects in preliminary tests (Schaider et al., 2017a). PFHxA incidence in food contact materials and composts is discussed in [*Focus Question #1*](#).

Table 2. PFAS terms and names referenced.[*]

Acronym	Complete name(s)	Examples
PFAS functional groups		
PFAAs	Perfluoroalkyl acids	PFCAs, PFSAs
PFCAs	Perfluoroalkyl carboxylic acids; Perfluoroalkyl carboxylates	PFOA
PFSAs	Perfluoroalkane sulfonic acids; Perfluoroalkane sulfonates	PFOS
FTOHs	Fluorotelomer alcohols	6:2 FTOH PAPs, diPAPs
FTCAs	Fluorotelomer carboxylic acids	5:3 FTCA
FTUCAs	Fluorotelomer unsaturated carboxylic acids	6:2 FTUCA
PAPs	*n*:2 polyfluoroalkyl phosphoric acid esters; Polyfluoroalkyl phosphates; Fluorotelomer phosphates	diPAPs, 8:2 monoPAP
diPAPs	Polyfluoroalkyl phosphoric acid diesters	8:2 diPAP
FASAs	Perfluoroalkyl sulfonamides	FOSA
FASAAs	Perfluoroalkane sulfonamido acetic acids	EtFOSAA
FTABs	Fluorotelomer sulfonamidoalkyl betaines	6:2 FTAB
Individual substances		
PFOA	Perfluorooctanoic acid	
PFOS	Perfluorooctanesulfonic acid	
FOSA	Perfluorooctane sulfonamide	
PFAB	Perfluorobutanoic acid	
PFHxA	Perfluorohexanoic acid	
PFHpA	Perfluoroheptanoic acid	

[6] Homologs are compounds with the same set of functional groups (*e.g.,* one hydroxy group (-OH)), yielding similar properties but consisting of different repeating units (*e.g.,* carbon chain length).

Acronym	Complete name(s)	Examples
PFPeA	Perfluoropentanoic acid	
8:2 FTCA	8:2 fluorotelomer carboxylic acid	
5:3 FTCA	5:3 fluorotelomer carboxylic acid	
6:2 FTOH	6:2 fluorotelomer alcohol	
8:2 FTOH	8:2 fluorotelomer alcohol	
PFBA	Perfluorobutanoic acid	
6:2 FTS	6:2 fluorotelomersulfonic acid	
6:2 FTUCA	6:2 fluorotelomer unsaturated carboxylic acid	
FASE	Perfluoroalkane sulfonamido ethanol	
FOSA	Perfluorooctanesulfonamide	
EtFOSAA	Ethylperfluorooctane sulfonamidoacetic acid	
6:2 FTAB	6:2 fluorotelomer sulfonamide alkylbetaine	

***Sources:** (Buck et al., 2011; Saha et al., 2024; A. S. Timshina et al., 2024)

<u>What is the history of PFAS in food contact materials?</u>

The Food and Drug Administration (FDA) first approved PFAS for food packaging use in 1967 (Rihn et al., 2024). The FDA continues to authorize PFAS substances through food contact substance notifications (Scholl et al., 2025).

In 2011, major manufacturers in the United States voluntarily phased out production of PFOA and PFOS because of their linkage to adverse health effects (Choi et al., 2019; Scholl et al., 2025). The phase-out resulted from the global PFOA Stewardship Program, initiated by the U.S. EPA, where long-chained polyfluoroalkyl carboxylic acids (PFCAs) were discussed (Eriksson & Kärrman, 2015). The PFAS industry then shifted to using shorter-chain PFAS and fluorotelomer-based PFAS (Buck et al., 2011; Eriksson & Kärrman, 2015).

The PFAS Action Acts of 2019 and 2021 directed the EPA to designate PFOA and PFOS as hazardous substances and to determine whether other PFAS should be classified under the same designation (Rep. Dingell, 2021; US EPA, 2019a). PFOA and PFOS were officially designated as CERCLA hazardous substances in July 2024 (US EPA, 2024c).[7] Ongoing toxicity decisions can be seen in the EPA's Toxic Release Inventory; the Toxic Release Inventory does not designate hazard status but instead tracks substances that may cause (US EPA, 2013):

- cancer or other chronic human health effects
- significant adverse acute human health effects
- significant adverse environmental effects

A second voluntary manufacturer phase-out began in 2021, targeting 6:2 FTOH, a fluorotelomer-based PFAS in food packaging, due to concerns about the toxicity of its metabolites (Phelps et al., 2024). The FDA announced the completion of the 6:2 FTOH manufacturer phase-out in February 2024 and indicated that a voluntary market phase-out for all PFAS used in grease-proofing will follow as a response to an increasing number of studies showing food packaging PFAS transfer to food (US FDA, 2024, 2025). According to the Federal Register Notice published on January 6, 2025, the FDA will remove 35 food contact substance notifications related to food contact surfaces containing PFAS in paper and paperboard food packaging by June 30, 2025 (90 FR 653, January 6, 2025). This is due to manufacturers or suppliers having ceased the production, supply, or use of these substances. The FDA announcements acknowledge that it could take up to 18 months after the last date of sale to exhaust the market supply.

As of December 2024, the EPA's PFAS Toxic Release Inventory includes 196 PFAS (US EPA, 2019b). As a comparison point, two separate EPA lists describe over 16,000 PFAS structures (US EPA, 2022, 2024b). The EPA has not designated other PFAS as hazardous substances at 40 CFR part 302 beyond PFOA and PFOS, their salts, and structural isomers (US EPA, 2024c). Because most PFAS are not considered hazardous substances, they are not required to be reported on safety data sheets (Tryon, 2022). Limited information is available regarding the toxicity and environmental fate of newly identified PFAS (Munoz et al., 2022).

<u>What challenges are there with testing for PFAS?</u>

Testing for fluorinated substances is not straightforward (Thijs et al., 2024). No single method can quantify or identify all PFAS, their impurities, and degradation products, nor can it differentiate PFAS from other fluorine-containing materials (Thijs et al., 2024). Researchers are interested in developing tests that can quantify and identify specific PFAS compounds, using reference chemicals or "standards" (Stroski et al., 2024). These tests are known as

[7] CERCLA stands for the Comprehensive Environmental Response, Compensation, and Liability Act, also known as Superfund.

targeted analyses. Currently, researchers have developed targeted analyses that can identify about 30 – 40 PFAS (Stroski et al., 2024). This leaves any other PFAS, impurities, and degradation products unaccounted for.

One difficulty in understanding the potential for compostables to introduce PFAS into compost is that identifying the presence and concentration of PFAS is a challenge. Several authors note that quantifying PFAS and making comparisons between studies is difficult, even when only a single type of PFAS is involved (Phelps et al., 2024; Stroski et al., 2024; Thijs et al., 2024). Measured concentration values are affected by a variety of factors, including (Phelps et al., 2024; Schaider et al., 2017a; Stroski et al., 2024; Thijs et al., 2024; A. Timshina et al., 2021):

- extractions methods
- instrumentation
- targeted analytes
- impurities, such as unreacted monomers
- degradation products
- relative solubility of the substances analyzed
- PFAS volatility in samples used

Researchers have tried to overcome these challenges in a few ways. They have started to create non-targeted analyses, which do not rely on specific PFAS reference chemicals (Stroski et al., 2024; Thijs et al., 2024). Instead, the analyses use different tools to search for chemical structure patterns. Non-targeted analyses expand the range of what can be detected, especially those that do not require an extraction step (Stroski et al., 2024; Thijs et al., 2024). However, many of these methods are currently limited because the technology behind them is still relatively new, affecting the analysis stability, accuracy, and repeatability (Y. Cui et al., 2024).

Another way to address the difficulty of determining the presence and concentration of PFAS is by focusing on specific targeted analysis issues, like PFAS volatilization loss. For example, researchers developed a saponification-based method specifically to aid in 6:2 FTOH volatilization loss (Scholl et al., 2025). The FDA announced that this analysis method will be used for their 6:2 FTOH market screening (Scholl et al., 2025; US FDA, 2025). However, this analysis method is still limited in providing quantitative measurements (Scholl et al., 2025).

Despite these detection limitations, multiple studies have assessed the prevalence of elevated PFAS levels and investigated the presence of PFAS in commercial products. We summarize fluorine and PFAS detection in the context of composts in *Focus Question #1*.

Focus Questions

Focus Question #1: Summarize available research on the potential for compostable synthetic food Packaging plastics and cellulosic fiber-based materials (“compostables”) to introduce additional PFAS into composting systems.

Synthetic food packaging plastics and cellulosic fiber-based products are often made with per- and polyfluoroalkyl substances (PFAS) (Goossen et al., 2023; Stroski et al., 2024; A. S. Timshina et al., 2024). PFAS are primarily referenced by their initialisms (see *Table 2*). The addition of PFAS is due to the necessity for resistance to grease, oil, and water in these products (Semple et al., 2022). PFAS are among the cheapest and most effective solutions for these sought-after qualities. Researchers prioritize PFAAs when discussing PFAS’ toxicological concerns (Choi et al., 2019; A. S. Timshina et al., 2024). PFAAs are commonly referred to as “terminal PFAS” because they are unlikely to degrade further under typical environmental conditions.

Though they are considered to be ubiquitous substances, additional PFAS are introduced into composts via a variety of non-food contact materials (Khair Biek et al., 2024; A. S. Timshina et al., 2024):

- feedstock materials
- fertilizers, especially when blended with compost
- pesticides
- tarps and mulches
- water
- re-used transport bins
- dust

Some of these non-food contact materials, like fertilizers, introduce additional PFAS by containing PFAS themselves (Khair Biek et al., 2024; Schaider et al., 2017a). For example, fertilizers and pesticides can be produced from plant materials that contain PFAS, which bioaccumulated in tissues. Manufacturers also use PFAS in pesticides and herbicides, serving as both active and inert ingredients (Khair Biek et al., 2024). However, according to Timshina et al. (2024), PFAS concentrations from non-food contact material feedstock sources are probably negligible compared to concentrations that come from plant-fiber food contact materials (*e.g.,* paper plates and bowls).

PFAS do not readily decompose during composting due to the strength of their carbon-fluorine bonds (see the Background section, *What are per- and polyfluoroalkyl substances (PFAS), and how are they used in compostables?* above). Once applied to a food packaging or other product, long-chain PFAS degrade and form PFAAs (Choi et al., 2019). For example, FTOHs, FTSs, and PAPs are long-chain PFAS that form PFAAs. In an aerobic environment, these three types of long-chain PFAS biodegrade in a half-life range of less than a day to a few years (Choi et al., 2019).

Are PFAS present in compostable materials?

Compostables are a source of PFAS in compost (Choi et al., 2019; Goossen et al., 2023; Khair Biek et al., 2024; Munoz et al., 2022). Food contact materials marketed as "eco-friendly" and/or "compostable" can have greater PFAS concentrations than their non-compostable marketed counterparts (A. S. Timshina et al., 2024). Researchers most frequently find PFAB, PFOA, and FTOHs in these products (Choi et al., 2019; Goossen et al., 2023; Schaider et al., 2017a), and PAPs are one of the most extensively used (A. S. Timshina et al., 2024).

Examples of common cellulosic fiber-based products that may contain PFAS include (Khair Biek et al., 2024; Schaider et al., 2017a; Semple et al., 2022):

- molded pulp take-out packages
- baking parchment
- burger wraps
- microwave popcorn bags
- paper cups
- paper boxes and bags
- paper plates and bowls
- wrappers
- paperboard

The concentration and relative abundance of PFAS in a compostable product depends on the intended use (*e.g.,* greasy food receptacle, straw, utensil, etc.) (Choi et al., 2019).[8] Products designed for greasy foods are more likely to have higher PFAS concentrations. Manufacturers in different countries use and produce different PFAS compounds as well (Schaider et al., 2017a). For example, manufacturers in the United States rely on 6:2 FTOH as the most common FTOH, whereas manufacturers in China more commonly use longer-chain FTOHs. Long-chain PFAS phase-out has not occurred in China (Schaider et al., 2017a).

Manufacturers do not use equal amounts of PFAS in all compostable materials (Semple et al., 2022). Some materials naturally possess hydro- and/or oleophobic properties, or they can be combined to achieve the desired characteristics (Jandas et al., 2019; Semple et al., 2022):

- Bagasse fiber
  - Disposable tableware made from unbleached bagasse fiber requires a 2% addition of a fluoride-based oil-resistant agent, usually PFAS.
  - Bagasse and bamboo combined fiber reduces or eliminates the need for PFAS.
- Cellulosic fiber
  - Cellulosic fiber-based products like molded pulp are treated with PFAS at the pulp stock stage to bond fibers and increase hydro- and oleophobicity.
  - Enzymatic hydrolysis lignin increases tensile strength and hydrophobicity, eliminating the need for PFAS in molded pulp.
- Polylactic acid (PLA)
  - Virgin PLA is naturally hydrophobic and requires no additives to achieve this property.

PFAS additives work by repelling water and oil from the substrate (Semple et al., 2022). Alternatives generally focus on restricting the flow of water and oil rather than repelling it. Alternatives include substances like bio-based starches and waxes (Semple et al., 2022).

[8] Bear in mind that accurately measuring concentration of PFAS is difficult.

As discussed in the background section on PFAS (*What challenges are there with testing for PFAS?*, *above*), an absolute testing method does not currently exist to differentiate between PFAS and other fluorine-containing compounds. Current testing methods cannot precisely distinguish between the intentional addition of fluorine-based substances such as PFAS to food contact materials and unintentional background levels (Schaider et al., 2017a).

Schaider et al. (2017a) sampled various fast food packaging products for PFAS across the United States in order to measure the prevalence of PFAS in products potentially added to composts. The researchers detected fluorine in:

- 56% of bread and dessert wrappers
- 38% of sandwich and burger wrappers
- 46% of all food contact paper
- 20% of paperboard food packaging

There were no significant differences in the presence of fluorinated substances among the regions tested (Schaider et al., 2017a). The researchers also tried to gauge business proprietor awareness of PFAS in their manufactured products. In response to inquiries about PFAS use in their packaging by the researchers, two fast-food chains with high incidences declared that their packaging did not contain PFAS. Timshina et al. (2021) noted a similar response by United States straw manufacturers to inquiries about the presence of PFAS in paper and plant-based straws. Another fast food chain packaging company found that their products' PFAS concentration unknowingly exceeded 100 ppm due to the paper mill's fiber chemistry practices (Phelps et al., 2024). The company worked directly with the paper mill to address the issue, reportedly eliminating the need to add PFAS to manufacture the packaging product.

Timshina et al. (2021) examined the prevalence of PFAS in paper and bio-based straws sourced from the United States but manufactured in a range of countries including the United States, China, Mexico and Vietnam. Most of the brands tested marketed the products as compostable, biodegradable, or both. Products marketed as biodegradable included FDA logos specifying the product met these additional requirements. The authors stated that it was not possible to determine whether these claims were used appropriately. Though most straws examined were paper-based, bio-based straws included in the study were made from PLA, wheat stalk, avocado pit biopolymer, rice flour, and *Lepironia* reeds. PFBA and PFOA were both frequently detected across all straw types, regardless of material. Approximately 89% of the tested straws had measurable levels of PFOA, and approximately 28% contained PFOS. The researchers also found that straw wrappers contained PFAS, though there was no relationship between the type of PFAS present in wrappers and the PFAS in the straw materials. All materials tested measured below 100 ppm. However, the researchers indicated that due to the volatility of certain substances, further investigation is necessary to provide a more complete assessment of PFAS content.

Stroski et al. (2024) detected PFCAs, including long-chain PFCAs, in many types of materials using non-targeted analyses of food packaging. Long-chain PFCAs are rarely intentionally added in the United States. Other researchers have also detected PFAS intermediates, which can eventually degrade into terminal PFAAs, in food contact products like popcorn bags and combined plastic and paper films. These intermediates begin as less stable compounds and go through multiple intermediary stages before reaching their final degradation product. For example, two separate studies found that 6:2 diPAP undergoes chemical changes that produce several intermediate compounds including 6:2 FTUCA. These intermediates go on to form PFPeA, PFHxA, and PFHpA (Stroski et al., 2024).

Though single-use food contact materials are often made intentionally with PFAS (Goossen et al., 2023; A. S. Timshina et al., 2024), PFAS may also be added unintentionally as byproducts, impurities, or as a result of degradation products (Barhoumi et al., 2022). Many researchers think that substances that degrade to PFAAs, (like FTOHs and PAPs), are used in paper products rather than the non-degradable PFAAs (*e.g.,* PFOA) directly.

Are PFAS present in composts?

Choi et al. (2019) obtained composts from different sources and compared the PFCA and PFSA content in each: household bin waste compost, commercial compost where compostables are accepted, and commercial compost where compostables are not accepted. The researchers found that all compost types contained PFOA and PFOS (*Table 3*). However, they found that composts that included compostables had higher concentration of the terminal PFAS, PFAAs.

As a continuation of the Choi et al. (2019) study, Lazcano et al. (2020) compared PFAAs in composts from non-household waste feedstocks (manure, mushroom, peat, untreated wood) to composts with food and yard waste. Higher concentrations of PFAAs were found in food and yard waste compared to the other four types of compost. Nonetheless, the researchers found PFAAs in all feedstocks. They found that composts with higher organic carbon content have higher concentrations of PFAAs. Composts with manure had the highest concentration of PFAAs, followed by food and yard waste compost, and lastly, all other composts.

Table 3: Relative concentration of PFAAs in municipal composts. *Adapted from Choi et al. (2019).*

Type of compost	Concentration PFAAs (ppb*)	Concentration PFOA and PFOS (ppb)
Household bin	7.60	0.54 – 2.75
Commercial with compostables	31 – 75	7.94 –11.5
Commercial without compostables	<3.9	0.54 – <2.75

**parts per billion (ppb) = µg/kg*

Terminal PFAAs, such as PFOA, can come from precursors like FTOHs and FTSs through natural processes such as atmospheric oxidation and microbial degradation (Lazcano et al., 2020; Saha et al., 2024). As a result of this degradation, composting can increase concentrations of PFAAs (Choi et al., 2019). Dinglasan et al. (2004) tracked the aerobic degradation of 8:2 FTOH to PFOA using a mixed microbial system in lab conditions.[9] By day 7, 8:2 FTOH was 85% degraded. By day 16, the concentration of 8:2 FTOH fell below the 2-ppm detection limit, while PFOA was detected at very low levels.

Timshina et al. (2024) similarly tracked PFAS relative abundances in composts containing food contact materials. The compostables included:

- paper cups and plates
- bagasse clamshells
- bio-based plastic cups
- coffee pods labeled as being compostable
- pizza boxes

The food contact materials were collected alongside household kitchen and yard waste and were not removed from compost piles until after PFAS concentration baselines were established (see *Table 4*). This was meant to represent typical consumer behavior, where compostables maintain contact with household waste material for a period. Compost maturity influenced which compounds the authors detected. Mature composts showed lower concentrations of long-chain compounds, like PAPs, and higher concentrations of PFAAs, like PFHxA compared to earlier-stage compost. [10] The authors hypothesized that longer-chain compounds likely biodegraded into PFAAs throughout the composting process (A. S. Timshina et al., 2024).

Table 4: PFAS content in compost containing paper and plant-fiber compostables. *Adapted from A.S. Timshina et al (2024).*

Compost age (weeks)	Compound	Concentration (ppb)
Composting stage		
1	PAPs	1.1
	PFHxA	1.94*
	Total PFAS	**5.30 ± 2.77**
5	PAPs	0.55
	PFHxA	18.3
	Total PFAS	**23.1 ± 5.45**
Maturing/curing stage		
11**	PAPs	0.50
	PFHxA	18.5
	Total PFAS	**32.2 ± 27.2**
17	PAPs	0.76
	PFHxA	47.9
	Total PFAS	**84.3 ± 18.5**

The standard deviation measures variation in compost sample depth (see How do PFAS behave in composts?, below).
*Detected in 20% of samples only.
**Food contact materials removed.

How do PFAS behave in composts?

The depth at which a sample is taken within a compost pile and the moisture content of a compost pile will both impact the concentration of PFAS (Saha et al., 2024). The concentration of PFAS at the surface level is significantly lower than at deeper internal layers. This difference is due to various factors influencing the compost environment,

[9] The microbial species in this mixture were not described. However, the culture was specifically selected because it is known to degrade chlorinated carbon-based compounds and alcohols.
[10] PAPs analyzed were 6:2 diPAP, 6:2/8:2diPAP, and 8:2diPAP.

leading to short-chain PFAS migrating downward and away from the compost pile surface (Saha et al., 2024). These factors include:

- compost layer moisture differences
- higher vapor pressure at the surface of the compost piles
- PFAS water solubility trends
- PFAS soil adherence trends
- PFAA precursor transformation

Authors provide some explanation for how these factors are related to the chemical structure of PFAS (Saha et al., 2024; A. S. Timshina et al., 2024). Short-chain PFAS are more water-mobile and more volatile than substances with a longer carbon chain. Internal compost layers contain more moisture than surface layers, leading to a higher relative concentration of short-chain PFAS as these migrate downward alongside moisture (Saha et al., 2024). External factors such as precipitation at compost sites can also affect the migration of water-soluble PFAS in the compost piles (Saha et al., 2024; A. S. Timshina et al., 2024). Additionally, the high vapor pressure from the compost surface contributes to the volatilization of short-chain PFCAs, further reducing the relative concentrations of short-chain substances at the surface (Saha et al., 2024).

PFAS introduced into and degraded by composts can leach into the surrounding soil (A. S. Timshina et al., 2024). Rain events lead to PFAS leaching out of the compost pile and into the surroundings, leading to a decrease in these substances within the pile (A. S. Timshina et al., 2024). This water migration trend extends to other structural differences.

In addition to PFAS length, PFAS branching (or lack thereof) also influences PFAS characteristics (Saha et al., 2024). Structural branching can be controlled during manufacturing through electrochemical fluorination (*e.g.,* PFOS and PFOA) (Buck et al., 2011). Linear PFAS isomers tend to adhere to soil and sediments, whereas branched isomers are more prone to movement, using water as a vector for migration (Saha et al., 2024). This difference is attributed to a greater structural polarity in branched isomers than linear ones.

Long-chain PFAS adhere to solid matter like soil (Saha et al., 2024). Though the distribution of long-chain PFAS is also impacted by moisture (they have some water mobility), they have a higher affinity for dissolved organic matter (Saha et al., 2024; A. S. Timshina et al., 2024). The surface concentration of long-chain PFAS is higher relative to short-chain PFAS (Saha et al., 2024). Because long-chain PFAS adsorb to the organic material in the compost, they leach into the surroundings less (A. S. Timshina et al., 2024).[11]

The binding affinity of PFAS on organic matter is also affected by chemical functional groups and humification (Saha et al., 2024). The effect of PFAS on humification processes in compost are discussed in *Focus Question #3*.

Do PFAS interact with plastics (including microplastics) and compost?

Microplastics and PFAS are both polar molecules and contain variations in charge within their structures (Barhoumi et al., 2022). These charge variations exist on the plastic's surface (based on the type of plastic and how it was manufactured) and the PFAS functional groups charge (see *What is the composition and chemical structure of PFAS?* for more information). PFAS functional groups may be (Barhoumi et al., 2022):

- anionic (*e.g.*, PFCAs, PFSAs, FTCAs, and FTSAs)
- cationic (*e.g.*, FtTHN+ and FtSaAm)
- both anionic and cationic (*e.g.*, FTABs)
- neutrally charged (*e.g.,* FTOH, FASE, and FASA)

Due to small electromagnetic charges, polar molecules can attract or repel each other, depending on how they are oriented and the conditions of the chemical environment (Barhoumi et al., 2022; Junaid et al., 2024). This leads to PFAS binding to microplastics through weak bonds that are easily disrupted (Junaid et al., 2024). In cases where PFAS have a split charge, the interactions between PFAS and plastics are described by researchers as undergoing a "partitioning effect" (Barhoumi et al., 2022). In these cases, some PFAS molecules are dissolved and absorbed by the plastic because of the stronger attraction. For example, a positively polarized microplastic surface will more easily interact with a negatively polarized PFAS (Barhoumi et al., 2022). Absorption and adsorption can occur simultaneously.

Plastics, like bags used for yard waste, can act as carriers of PFAS because PFAS adsorb to the plastic's surface (Saha et al., 2024). The composting process may also create microscopic cracks in plastic that further increase the

[11] Adsorption: a surface interaction where molecules are attracted to the surface and do not penetrate the substrate material.

surface area, increasing the adsorption rate (Saha et al., 2024). PFAS adsorption to plastics can be further enhanced by the presence of organic matter (Junaid et al., 2024). Organic matter rearranges the location of bonding forces by creating greater dispersion and increasing the amount of available interaction sites. The adsorption enhancement cannot be generalized and depends on competition for adsorption sites, which can be affected by the factors described below (Barhoumi et al., 2022).

The increase in interactions increases the toxicity of microplastics and PFAS by influencing trophic transfers (Junaid et al., 2024).[12] PFAS can be taken up by growing plants and consumed by earthworms (Bolan et al., 2021; US EPA, 2021). Plants preferentially take up short-chain PFAAs and are more likely to bioaccumulate in the food chain despite having shorter half-lives than their longer counterparts (Choi et al., 2019). However, the exact trophic transfer mechanisms remain unknown (Junaid et al., 2024). Several factors may influence the adsorption capacity of microplastics (Barhoumi et al., 2022):

- cation presence and the pH of the compost
- PFAS structure
- type of plastic

As pH increases, microplastics develop a negative polarity charge and adsorb PFAS less (Barhoumi et al., 2022). However, the presence of cations increases the sorption of PFAS to microplastics by establishing a bridge between the negatively polarized PFAS and the plastic surface. Researchers have observed in several studies using calcium chloride and sodium chloride on polyethylene and polystyrene (Barhoumi et al., 2022). Anions like chloride and sulfate have the opposite effect, competing with PFAS for adsorption sites and thus decreasing PFAS sorption.

The adsorption of PFAS on the microplastic surface also depends on the concentration and nature of the organic matter present, the molecular size of the organic matter, and the exact properties of the PFAS and microplastic (Barhoumi et al., 2022). Organic matter may provide an environment that induces structural change in the microplastic, inhibiting or enhancing PFAS sorption. For example, some researchers have found that humic acid competes with PFAS for binding plastic (Barhoumi et al., 2022).

Focus Question #2: Do ASTM D6400, D6868 and D8410 standards ensure that compostables are fully metabolized (not simply broken down into fragments) by microorganisms when composted? If so, how do they ensure this?

In the course of our review of the available research into the ASTM standards (and their equivalents) referenced in the petition to add a definition of "Compost Feedstock" (Biodegradable Products Institute (BPI), 2023), we encountered an extensive range of results and conclusions as to whether these standards ensure that compostables are fully metabolized. There is no definite consensus in the literature regarding the suitability of the standards to ensure compostability in real-world settings due to many factors including:

- the chemical composition of the compostable material itself
- the surrounding environment (the compost pile itself and the physical environmental conditions)
- the variability of microbial populations in compost
- abiotic variables (mechanical breakdown, exposure to sunlight, and temperature conditions)
- difficulties in accurately measuring microbial metabolites in large-scale composting operations

The standards do not require absolute biodegradation. Instead, they generally require 90% of the material's weight to be disintegrated to below 2.0 mm particles (after 84 days), and that 90% of the material's organic carbon has been converted to carbon dioxide by microbial metabolization (after a minimum of 45 days) in small-scale tests conducted in a laboratory (ASTM International, 2021d, 2021b, 2021c, 2021a).

In the following subsections, we discuss the ASTM methods themselves, what they require, and what other standards they incorporate to verify their specifications. We describe the differences between disintegration, biodegradability, and compostability, and the physical and chemical processes facilitating them. We ultimately discuss the available literature exploring the verification of the standards, their limitations, and their suitability in laboratory and full-scale composting settings.

What do the standards specify, what methods do they use, and what does incorporation by reference mean?

The petition currently under consideration by the NOSB cites three ASTM standards (Biodegradable Products Institute (BPI), 2023). The full names of the cited standards appear below:

- ASTM D6400: *Standard Specification for Labeling of Plastics Designed to be Aerobically Composted in Municipal or Industrial Facilities*

[12] Trophic transfer: the movement of substances, including contaminants, from one level of the food chain to another.

- ASTM D6868: *Standard Specification for Labeling of End Items that Incorporate Plastics and Polymers as Coatings or Additives with Paper and Other Substrates Designed to be Aerobically Composted in Municipal or Industrial Facilities*
- ASTM D8410: *Standard Specification for Evaluation of Cellulosic-Fiber-Based Packaging Materials and Products for Compostability in Municipal or Industrial Aerobic Composting Facilities*.

The specifications contained in the standards are summarized below (see Table 5).

Table 5: ASTM standards cited in the petition, their summarized specifications, and other standards used to validate their specifications (ASTM International, 2021b, 2021c, 2021d)

Standard	Specified materials	Summarized specifications	Standards used to meet specifications
ASTM D6400	Plastics designed to be aerobically composted	Disintegration: no more than 10% of original dry weight remains after sieving on a 2.0 mm sieve after 84 days.	ISO 16929; or ISO 20200
		Biodegradation: 90% of the organic carbon shall be converted to CO_2 within 180 days.	ASTM D5338; or ISO 14855-1; or ISO 14855 – 2
		The product shall have concentrations of regulated metals less than 50% of those prescribed for sludges or composts in the country where the product is sold.	Table 3 of 40 CFR 503.13 (USA); or Table 1, compost category A, Guidelines for Compost Quality and category AA, Ontario Ministry of the Environment (Canada)
		Germination rate and plant biomass of sample composts shall be no less than 90% that of blank composts (without plastic).	OECD Guideline 208 with modifications found in Annex E of EN 13432
ASTM D6868	Items that incorporate plastics and polymers as coatings or additives with paper or other substrates designed to be aerobically composted	Disintegration: no more than 10% of original dry weight remains after sieving on a 2.0 mm sieve after 84 days.	ISO 16929; or ISO 20200
		Biodegradation: 90% of the organic carbon shall be converted to CO_2 within 180 days at 58 °C (±2 °C). Alternatively, over 95% of the item's carbon comes from biobased resources; biobased or organic polymers or additives blended with the ligno-cellulosic substrate comprising >1% dry weight of the item must be evaluated separately.	ASTM D5338; or, when inappropriate for the type of materials, ISO 14851, ISO 14852, and ISO 14855 ASTM D6866 (to fulfill 95% biobased threshold); ASTM D6400 (for biobased or organic additives >1%)
		The product shall have concentrations of regulated metals less than 50% of those prescribed in the associated regulation.	Table 3 of 40 CFR 503.13
		Germination rate and plant biomass of sample composts shall be no less than 90% that of blank composts (without plastic).	OECD Guideline 208 with modifications found in Annex E of EN 13432
ASTM D8410	Cellulosic-fiber based packaging materials and products	Disintegration: no more than 10% of original dry weight remains after sieving on a 2.0 mm sieve after 84 days; any remains must not significantly reduce the visual acceptability of compost.	ISO 16929; or ISO 20200
		Biodegradation: 90% of the organic carbon shall be converted to CO_2 within 180 days at 58 °C (±2 °C). Alternatively, over 95% of the item's carbon comes from biobased resources; any other organic component between 1-10% dry weight shall be evaluated independently for biodegradation.	ASTM D5338; or ISO 14855 ASTM D6866
		Germination rate and plant biomass of sample composts shall be no less than 90% that of blank composts (without plastic).	OECD Guideline 208 with modifications found in Annex B of ISO 18606
		The product shall have concentrations of regulated metals <50% of those prescribed in the associated regulation.	Table 3 of 40 CFR 503.13
		The product must contain ≥50% volatile solids content.	Standard Method 2540G; or USEPA Method 1684

All three standards rely on ASTM D5338, *Test Method for Determining Aerobic Biodegradation of Plastic Materials Under Controlled Composting Conditions, Incorporating Thermophilic Temperatures*, to demonstrate adequate biodegradation by composting (ASTM International, 2021d, 2021b, 2021c). It is unclear why ASTM D8410 cites ASTM D5338 since cellulosic-fiber-based packaging is not a plastic material, and ASTM D8410 specifically excludes items in which thermoplastic polymer is laminated or extruded onto cellulosic substances (such as in coatings) (ASTM International, 2021d). ASTM D5338 is discussed in greater detail below (see *Inset 1*). Several other standards are cited in the three ASTM standards (see *Table 5*), including:

- other ASTM standards
- Organization for Economic Development (OECD) standards
- International Organization for Standardization (ISO) standards
- Comite Europeen de Normalisation (CEN) standards
- U.S. Government (Standards as appearing in the Code of Federal Regulations)
- Canadian Government Standards
- Standard Methods for the Examination of Water and Wastewater
- USEPA methods

Inset 1: ASTM D5338-15R21; Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials Under Controlled Composting Conditions, Incorporating Thermophilic Temperatures, summarized

ASTM D5338-15R21 is the standard laboratory test method used to verify the aerobic biodegradation requirements described in ASTM D6400-21, ASTM D6868-21, and ASTM D8410-21, and is equivalent to ISO 14855.

Scope

The test method determines the degree and rate of aerobic biodegradation of plastic materials designed to be composted in facilities that achieve thermophilic temperatures. The test measures the percentage of organic carbon converted into carbon dioxide when materials are exposed to an inoculum derived from mature compost sourced from municipal solid waste, under controlled temperature, aeration, and humidity conditions. ASTM D5338-15R21 does not purport to represent a simulation of all composting conditions, only those operating under optimal conditions.

Apparatus and testing controls

The method requires the use of at least twelve vessels consisting of:

- one blank (mature compost inoculum only)
- one positive control (analytical grade cellulose powder mixed with compost inoculum)
- one negative control (polyethylene and compost inoculum)
- the test specimen mixed with inoculum

These four analytes must be replicated at least 3 times. Vessels must be 2 to 5 liters in volume, and the samples and polyethylene negative controls must be in the same form (powder, film, pellets, etc.). Polyethylene is used as the negative control because it is known not to biodegrade. Cellulose is used for the positive control because it is known to biodegrade under the conditions of the test.

Each vessel must be temperature controlled during the duration of the test to maintain a constant temperature of 58°C (±2°C). The vessels must also be connected to a pressurized air system providing carbon dioxide-free, water-saturated air when utilizing a capture and titration method. Alternatively, normal air is used when vessels are connected directly to carbon dioxide monitoring equipment. For capture and titration methods, each vessel must be connected to another vessel containing a barium hydroxide trap solution to absorb emitted carbon dioxide.

Procedure

The laboratory must obtain an inoculum of two to four month old compost from a composting plant and screen it to less than 10 mm. This inoculum is mixed with the samples or controls in a 6:1 ratio after contents of nitrogen, moisture, dry solids, and volatile solids are determined. The mixes are placed in the vessels, with adequate airspace for weekly shaking. Aeration begins, with careful control of oxygen levels at 6% or greater.

Vessels are stored in the dark for at least 45 days, or until technicians determine that observations can end. Carbon dioxide and oxygen levels are monitored throughout. At the end of the test, the contents of each vessel are weighed and tested for pH. pH lower than 7 (neutral), may invalidate the test, indicating the potential for "souring," in which excess volatile fatty acids are present.

For direct monitoring, such as gas chromatography, the volume of carbon dioxide may be directly calculated. For capture and titration methods, the remaining barium hydroxide must be neutralized by titration with hydrochloric acid, using phenolphthalein as a pH color indicator, to determine the volume of absorbed carbon dioxide. The barium hydroxide trap solution works to absorb carbon dioxide by the following equation, in which barium carbonate is an insoluble precipitate:

$$Ba(OH)_2+CO_2 \rightarrow BaCO_3+H_2O$$

Results are averaged among the replicates and standard errors and confidence intervals are determined using general statistical equations.

In some cases, our discussion of ASTM standards also applies to ISO standards. ASTM and ISO standards are equivalent in some circumstances. Briassoulis et al. (2010) provide an excellent overview and comparison of relevant ASTM, ISO, EN, DIN (Deutsches Institut für Normung), Italian norm, Japanese industrial, and Belgian standards.

The most common testing standards used to evaluate degradation of biopolymers in scientific research are ISO 14855-1:2012 and ASTM D5338-15 (Pires et al., 2022). The following standards are considered equivalent to each other:

- ISO 14855-1 (*Determination of the ultimate aerobic biodegradability of plastic materials under controlled composting conditions – Method by analysis of carbon dioxide*) is equivalent to ASTM D5338 (ASTM International, 2021a).
- ISO 17088 (*Plastics – Organic recycling – Specifications for compostable plastics*) is equivalent to ASTM D6400 (ASTM International, 2021b).
- ISO 18606.1.7 (*Packaging and the environment – Organic recycling*) is equivalent to ASTM D8410 (ASTM International, 2021d).

There is no ISO equivalent to ASTM D6868 (*Standard specification for labeling of end items that incorporate plastics and polymers as coatings or additives with paper and other substrates designed to be aerobically composted in municipal or industrial facilities*) (ASTM International, 2021c).

Adherence to ASTM standards is strictly voluntary. ASTM is not a regulatory agency, although regulatory agencies may incorporate ASTM standards by reference, thereby mandating compliance to them (ASTM International, 2024; Office of the Federal Register, 2023). The three ASTM standards referenced in the petition, ASTM D6400, D6868, and D8410 are specific to the labeling of manufactured products as "compostable," meaning that it is voluntary for packaging manufacturers to adhere to the standards. If NOP incorporated the standards by reference in the regulation, the regulation would mandate that manufactured products meet the labeling requirements to be used in the regulatory scheme for the intended purpose (Office of the Federal Register, 2023).

The process by which a federal agency may incorporate external standards by reference in a regulation is beyond the scope of this report but can be found at 1 CFR part 151 (47 FR 34108, August 6, 1982). In short, a federal agency may request that published data, criteria, standards, specifications, techniques, illustrations, or similar material be incorporated by reference in a final rule. The request may only be approved by the Director of the Federal Register (Office of the Federal Register, 2023). One requirement that must be verified by the Director is that the published material "is reasonably available to and usable by the class of persons affected." "Reasonably available to and usable" does not necessarily mean that the published material is available free of charge; some material must be purchased but some standards organizations offer materials incorporated by reference free of charge (Office of the Federal Register, 2024). However, some of the free material may be out of date because standards are continuously updated while the regulatory incorporation by reference is not (see *Focus Question #5* for more information about the ASTM standards revision process). ASTM D6400-12, ASTM D6868-11, EN 13432, and ISO 17088:2012 are currently incorporated by reference in 7 CFR 205.3 and cited as criteria for the evaluation of biodegradable biobased mulch films in 7 CFR 205.2, *Terms defined*. The numbers following the standard numbers (ASTM D6400-12, ASTM D6868-11, and ISO 17088:2012) refer to the years the standards were updated, demonstrating that standards incorporated by reference may be out of date since all of those standards have been amended since.

The ASTM standards cited in the petition do not describe any compliant composting techniques or methods beyond an assumption that aerobic conditions are maintained and thermophilic temperatures are reached (ASTM International, 2021c, 2021b, 2021d). The specifications for simulated composting conditions in the laboratory are described in ASTM D5338, which is referenced in the cited standards, but not directly in the petition. The three ASTM standards cited in the petition are requirements for the labeling of packaging and are not guarantees that the packaging will fully compost in all composting situations. The standards also stipulate that they only apply to "large scale aerobic municipal or industrial composting facilities." Researchers have found that home composting systems are generally inadequate to break down bioplastic materials labeled in accordance with ASTM D6400 or equivalent standards (Arikan & Ozsoy, 2015; Briassoulis et al., 2010; Dolci et al., 2024; Pires et al., 2022; Song et al., 2009).

What do the terms "disintegration," "biodegradation," and "compostability" mean, in the context of ASTM and related standards?

Two processes work to break down compostable materials: disintegration and biodegradation (Wyman & Salmon, 2024). Disintegration is a physical process while biodegradation is a chemical process, although the two processes often occur simultaneously.

- Disintegration (the process by which substances break down into smaller pieces) increases the rate of biodegradation because it increases the surface area exposed to microorganisms.
- Microorganisms biodegrade compostables, chemically breaking down the material.

Some literature refers to disintegration as "degradation" as opposed to "biodegradation" (Song et al., 2009).

Disintegration without biodegradation can result in the buildup of environmentally concerning microplastics and fiber fragments (Song et al., 2009; Wyman & Salmon, 2024). Hydrophobic polymer microplastics often migrate into the ecosystem (Song et al., 2009). These hydrophobic microplastics attract and hold toxic chemicals like polychlorinated biphenyls (PCBs) and dichlorodiphenyltrichloroethane (DDT) up to one million times background levels that would normally be diluted out in soil environments (Song et al., 2009). Hydrophobic bioplastics designed to disintegrate but not be assimilated by microorganisms have the potential to be more environmentally harmful than non-degradable plastics (Song et al., 2009).

ASTM standards require both disintegration and biodegradation to occur. Disintegration is measured with a sieving test in which the finished material is passed through a 2.0 mm sieve (ASTM International, 2021b, 2021c, 2021d). Samples exhibiting adequate disintegration will pass through, leaving no more than 10% of the original dry weight behind. The standards define adequate biodegradation as the condition when 90% of the organic carbon in the starting material has been converted to carbon dioxide.

ASTM D6400 defines "biodegradable plastic" and "compostable plastic" differently, based on ASTM D883, *Terminology Relating to Plastics* (ASTM International, 2021b):

- biodegradable plastic: a degradable plastic in which the degradation results from the action of naturally occurring microorganisms such as bacteria, fungi, and algae.
- compostable plastic: a plastic that undergoes degradation by biological processes during composting to yield CO_2, water, inorganic compounds, and biomass at a rate consistent with other known compostable materials and leave no visible, distinguishable or toxic residue.

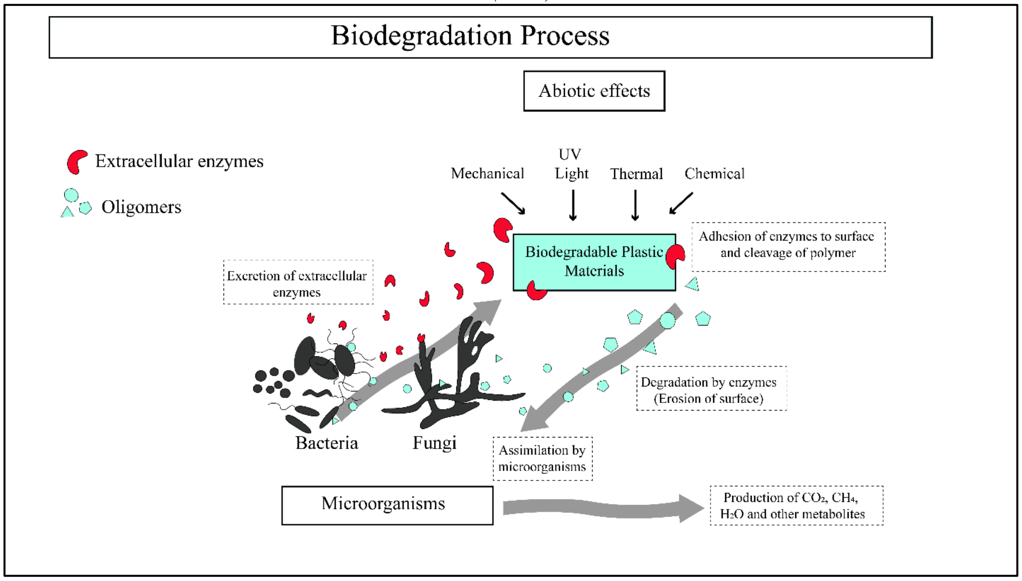
No single mode of action works to degrade or biodegrade compostable plastics. Physical mechanisms play a role in concert with microbial action. Some materials photodegrade, a process in which ultraviolet radiation exposure (such as from sunlight) breaks them down, either degrading them directly or exposing them to further bacterial degradation (Arikan & Ozsoy, 2015). Wyman & Salmon (2024) criticize lab-based compostability testing because photodegradation is minimal in the laboratory setting. Polymers can become resistant to biodegradation through the action of light, due to cross-linking (photopolymerization). Photopolymerization can occur in the field or in a compost facility, potentially increasing the persistence of plastic fragments (Anunciado et al., 2021; Song et al., 2009).

The polymeric structure of a substance generally governs its rate of degradation (Muniyasamy et al., 2013). Hetero-chain polymers, or polymers in which the backbone is composed of carbon along with other non-carbon atoms (for example, polylactic acid), typically biodegrade through hydrolysis initiated by esterase enzymes (chemicals that break ester bonds) excreted from microorganisms. Biodegradation through ester hydrolysis of hetero-chain polymers may be as short as one month; however, the rate can be controlled by adding other ingredients to suit particular end uses (Muniyasamy et al., 2013).

Carbon backbone polymers, or polymers in which the entire repeating chain is carbon-based (such as rubber), are generally degraded through oxidative mechanisms (Muniyasamy et al., 2013). Oxidative (or oxidative enzyme-mediated) biodegradation typically involves the oxidation of functional groups on the polymer by peroxidase enzymes (chemicals that break down peroxides by cleaving the oxygen-oxygen bonds) produced by fungi or actinomycete bacteria. Oxidative biodegradation may take years (Muniyasamy et al., 2013).

Some natural polymers like lignin and rubber only undergo oxidative biodegradation, while others like polysaccharides or proteins only undergo hydrolytic biodegradation (Muniyasamy et al., 2013). In both hydrolytic or oxidative degradation, the ultimate fate of the fragmented polymers in an idealized biodegradation process is a reduction in size so the substances can pass through the microbial cell membrane to be metabolized (Muniyasamy et al., 2013) (see *Figure 4*).

Figure 4: Disintegration by enzymes, degradation by abiotic effects, and biodegradation of plastic. *Adapted from Pires et al. (2022).*



Microorganisms directly assimilate some compostable bioplastics (Pires et al., 2022). In other cases, microorganisms indirectly degrade them using secreted enzymes (Pires et al., 2022). The resulting oligomers from surface degradation may or may not be directly assimilated by microorganisms. Some polymers can only be broken down by thermophilic microorganisms, but the resulting products can only be consumed/used by mesophilic microorganisms (Ruggero et al., 2019).

To further complicate the situation, each engineered bioplastic differs in its structure and chemical composition (Pires et al., 2022). Organic or inorganic nanomaterials, or antioxidant and antimicrobial essential oils and extracts may be incorporated in the structure to more closely mimic the characteristics of conventional plastic packaging (Pires et al., 2022). Additives often reduce the degradation rate. Additionally, many new materials are composites of bioplastic and lignocellulosic material, greatly altering the biodegradation characteristics (Muniyasamy et al., 2013; Pradhan, Misra, et al., 2010; Pradhan, Reddy, et al., 2010).

Additionally, some manufacturers have pursued the development of "oxo-degradable" plastics. Manufacturers create these using traditional plastics from petroleum-derived raw materials to manage costs, but add other substances to the polymer chain to promote oxidation by moisture or sunlight (Abdelmoez et al., 2021). Additives are typically transition metals like nickel, iron, manganese, and cobalt or their salts, which oxidize and facilitate breakage of the polymer chain, with the goal that particles become small enough that microorganisms can consume them (Abdelmoez et al., 2021). Some research indicates that oxo-degradable plastics are sufficiently microbially biodegraded in soil environments but, interestingly, not in compost (Abdelmoez et al., 2021; Chiellini et al., 2003; Jakubowicz, 2003). Other researchers have found evidence that oxo-degradable plastics are only broken down physically into minuscule microplastic fragments (Abdelmoez et al., 2021; Musioł et al., 2017; Yashchuk et al., 2012). For example, one research team found that a linear low density polyethylene (LLDPE) mulch film with pro-oxidants persisted in a soil environment as invisible micro-fragments even after 8.5 years without any chemical modification (Briassoulis et al., 2015). They hypothesized that these tiny fragments had the potential to enter the respiratory systems of animals. Oxo-degradable plastics are prohibited under Article 5 of European Union *Directive (EU) 2019/904 of the European Parliament and of the Council of 5 June 2019 on the reduction of the impact of certain plastic products on the environment* (2019) due to the risk of microplastic pollution.

<u>Do the standards ensure compostability?</u>

Some researchers argue that the lab-scale methods described in ASTM and ISO standards are insufficient to demonstrate biodegradability of bioplastics in working composting sites (Folino et al., 2023; Pires et al., 2022; H. Zhang et al., 2017). Pires et al. (2022) and da Silva et al. (2024) reviewed studies of bioplastic degradation from different authors. Pires et al. and da Silva et al. both noticed that authors reported different biodegradability rates for the same polymers, using the same ASTM or ISO biodegradability standards. They concluded that the authors used additional lab methodologies not described in the standards at certain steps. Other researchers have also recognized variation from the method standards in the body of research on the topic (da Silva et al., 2024; Ruggero et al., 2019; Wyman & Salmon, 2024). Wyman and Salmon (2024) noted the need for additional research to validate small-scale compostability testing, and that laboratory testing may have limited relevance in real-world applications. Briassoulis et al. (2010) proposed entirely separate testing methods and labeling standards for compostable biopolymer feedstocks composted on-farm, coopting aspects of several international standards.

A new ASTM method is under development to assess disintegration of compostable materials in real-world conditions (Compost Research and Education Foundation, n.d.-a). Importantly, ASTM WK80528, *Standard Field Test Method to Assess Disintegration in Defined Real-World Conditions* will only evaluate whether or not compostable items disintegrate, not if they will biodegrade and microbially mineralize (Compost Research and Education Foundation, n.d.-b).

Kunioka et al. (2006) reported different biodegradability results determined by different companies or organizations using the same standard methods, and stated that the data cannot be compared. ASTM D5338 and the equivalent ISO standard, ISO 14855-1, require the use of powdered cellulose as the positive reference control material in the laboratory procedure (ASTM International, 2021a; Kunioka et al., 2006). However, many biodegradable polymers are aliphatic polyesters (including polylactic acid) or starch composites, which are enzymatically degraded by hydrolases or lipases, while cellulose is degraded by cellulases (Kunioka et al., 2006; S. Li & Vert, 2002; Sintim et al., 2020).[13] For this reason, Kunioka et al. (2006) stated that the reference material and sample material are degraded differently, leading to concerns about the appropriateness of the experimental control.

Folino et al. (2023) explored the criteria required by various international standards used for lab-scale compostability testing of biopolymers, including ASTM, ISO, and EN standards. They concluded:

> …it appears that biodegradation standards were addressed more in order to demonstrate that bioplastics are the panacea for solving the problems related to plastic pollution rather than providing an environmentally sound tool for the purposes of evaluating the properties of a given material. In fact, the available literature often demonstrates that biodegradation in real environmental or plant conditions is lower than expected and sometimes negligible.

Many biopolymers meet the requirements of the lab standards, but researchers find inconsistent results in real compost environments due to the potential for environmental conditions to vary (Sintim et al., 2020). Laboratory conditions are controllable, in contrast with variable environmental and microbiological conditions in natural and industrial environments (Folino et al., 2023).

Full or field-scale research into biopolymer biodegradability is comparatively rare (Folino et al., 2023). Furthermore, researchers may interpret the results of field tests differently from lab studies, because the procedures are not the same as the standardized methods (Folino et al., 2023). For example, in real composting conditions, it is not currently possible to accurately measure how much CO_2 is released, so proxy measurements must be used to assess biodegradation, such as (Sintim et al., 2020):

- surface area measurements
- FTIR spectroscopy
- thermal gravimetric analysis (a mass change test related to stability of polymers in a temperature range)
- NMR
- molecular weight analysis

Literature examining the suitability of ASTM D8410 as a standard for third-party certifiers to evaluate the compostability of cellulosic-fiber-based packaging materials in municipal or industrial facilities is exceedingly scarce, as is research exploring the equivalent standard ISO 18606. All mentions of ASTM D8410 we encountered during the research for this report was instead related to bioplastics and not paper-based packaging. Some research is available regarding the compostability of bleached and unbleached paper-based products, as well as paper coated with biopolymers, however, sometimes citing ASTM D5338 as the test method or other equivalent international methods.

Lab-scale research shows that bleached, uncoated paper products degrade in compost most readily (Dolci et al., 2024; Michel et al., 2004). Unbleached, uncoated paper resists disintegration and biodegradation more than bleached paper. Unbleached paper with biopolymer coating degrades most slowly, sometimes not meeting the requirements of ASTM D5338. The bleaching process works to remove lignin from paper, and lignin is recalcitrant to biodegradation (Dolci et al., 2024). Rather than fully transforming into compounds like CO_2, water, and biomass,

[13] Specifically, proteinase K (excreted by certain fungal species), pronase, esterase, and bromelain (from pineapple) are examples of hydrolase enzymes that accelerate degradation of polylactic acid (S. Li & Vert, 2002). Aliphatic polymers are bioplastics derived from precursors such as lactides, glycolides, and ε-caprolactone.

lignin may instead be broken down into fragments that contribute to the formation of humic substances in compost (Tuomela et al., 2000; Venelampi et al., 2003).

Alvarez et al. (2009) conducted simulations in the laboratory corresponding to the requirements of UNE-EN 14046 (*Evaluation of the ultimate aerobic biodegradability of packaging materials under controlled composting conditions*), which correspond with ISO 14855 (itself equivalent to ASTM D5338) to test the compostability of several different paper products against a microcrystalline cellulose positive control. The researchers, located in Spain, noted that composting facilities there generally produce poor quality compost, and accept a relatively high volume of paper material (12-27% dry weight) compared to organic waste. They found that none of the paper tested achieved the biodegradability of the cellulose positive control after 45 days. They concluded that only white paper (such as copy-machine paper) and recycled paper are appropriate as compost feedstocks at the volumes simulated but should be composted for greater than 45 days. They considered cardboard, tissue (such as napkins), and newspaper to be insufficiently biodegradable at these volumes, and kraft paper (such as paper bags) to be effectively non-biodegradable (Alvarez et al., 2009).

According to Pires et al. (2022), the variability of biopolymer chemical structure, the inclusion of additives, and surrounding environmental conditions may alter the biodegradation rate of compostables. Researchers urge regulators to develop legislative standards that incorporate additional compositional analysis beyond CO_2, mass-loss, and physical characteristics of the material throughout the composting process (Pires, 2023; Pires et al., 2022). They suggested these comprehensive standards be developed using in situ ecotoxicological assessments rather than lab-scale studies alone. Pires (2023) also noted the need for researchers to identify which microbial taxonomic classes produce the most adequate enzymes to degrade polymers.

<u>How do compostables degrade in full-scale composting environments?</u>
Although they are more rare than studies exploring lab-scale simulations, we found several studies designed to assess compostability of biopolymer, paper, and composite materials in real composting conditions.

Mörtl et al. (2024) designed a large scale experiment to evaluate the disintegration and biodegradation of certified compostable carrier bags consisting of 20% starch, 10% undisclosed additives, and 70% polybutylene adipate terephthalate (PBAT). They used the maximum mass of biopolymer compared to other commonly composted materials like manure and wood, while still maintaining necessary C:N ratio to sustain composting. This was an attempt to mimic industrial-scale amounts of biopolymer in a realistic composting environment as opposed to the majority of existing scientific literature which uses far smaller quantities. They found that the degree of disintegration of the bags to particles below 2 mm reached 95% after 12 weeks. However, they also found that those microplastic particles did not fully biodegrade after one year, persisting as intermediate metabolites or monomers. They also observed statistically insignificant germination inhibition of white mustard, spring barley, and Chinese cabbage seeds when using the finished compost. The biomass of those germinated seeds, however, was significantly reduced in spring barley and white mustard.

Biodegradable mulch films are often manufactured using the same biopolymers used in compostable food packaging, such as PLA, PHA, and PBAT. These films are often colored with the additives carbon black or titanium dioxide to enhance performance in the field (Sintim et al., 2019; Yu et al., 2022). While little is known about carbon black's toxicity to micro- and macroorganisms or fate in terrestrial ecosystems, titanium dioxide nanoparticles have been shown to be toxic to a wide range of micro- and macroorganisms (Hou et al., 2019; Sintim et al., 2019). Researchers have observed likely residues of carbon black and definite residues of titanium dioxide micro- and nanoparticles following composting of colored biodegradable mulch films, indicating that non-biodegradable additives may accumulate in compost containing biopolymer feedstocks (Sintim et al., 2019; Yu et al., 2022).

Venelampi et al. (2003) observed entirely different decomposition rates for bleached and unbleached recycled paper hand towels in full-scale windrow experiments. Degradation differences were apparent even among the same types of samples depending on how the sample was introduced to the compost pile: direct addition, attached to steel frames, or placed inside mesh bags. They also observed degradation differences in replicates of the same experimental setups.

Zhang et al. (2017) explored the disintegration, but not ultimate biodegradation, of a wide variety of compostable products in real-world composting facilities, including kraft paper, PLA cutlery, PLA drinkware, PLA clamshell-style boxes, cellulose bags, and various plant fiber-based serviceware (uncoated and PLA coated). They found all of these products disintegrated (not biodegraded) efficiently under in-vessel and static pile composting conditions and met the disintegration requirements of ASTM D6868. In windrow conditions, only the solely PLA products disintegrated. Paper and paper coated with PLA barely broke down at all in windrows, which the researchers attributed to insufficient moisture levels. However, this study did not explore microbial biodegradability by evolution of carbon dioxide or proxy methods, so we cannot conclude that the substances that disintegrated were mineralized or incorporated into microbial biomass; only that they were broken down to particles below 2 mm. Some other literature consulted for this report appears to conflate the disintegration part of the tests with biodegradability, but this is incorrect because it does not necessarily indicate microbial metabolization, only breakdown into smaller particles.

Focus Question #3: Summarize any available research that indicates whether compostables are toxic to microorganisms in compost piles. Are there any studies that indicate whether these substances impact the diversity of microorganisms present in composting systems?
According to Afshar et al. (2024), it is challenging to develop a comprehensive overview of the performance and environmental impacts of biodegradable plastics due to the variety of plastic types and products, as well as their continued development. Thoroughly evaluating the microbial agro-ecotoxicology of these materials is an enormous undertaking that exceeds what is possible to encompass within a technical report. In order to make this manageable, we focused on a handful of commonly used compostable plastics. Very little research on the microbial toxicology of these substances is available, but we found some information on the effects of compostable materials on microorganism communities.

The literature we reviewed (described below) indicates that the effects of compostable materials on microorganisms are varied. Furthermore, some studies have shown that compost created from compostable materials can have negative effects on plants.

Compostable materials do have some commonalities. Some of these polymers break down into substances that can change the pH or soil or compost. Some can also affect nutrient cycling, especially nitrogen. The inclusion of compostable materials can create shifts in the diversity of microorganisms present in soils, and also in compost. However, composts naturally undergo shifts in microbial communities.

What microorganisms are typically present in compost, and what are their normal population dynamics?
In order to compare the effects of compostables on microorganisms in compost, we need to have a baseline for how compost typically forms and behaves. Much of the following information relies on an excellent review on the microbiology of composting by Kutzner (2001). This information is consistent with other literature we reviewed on the subject.

Microorganism communities in compost change over time, depending on the phase and maturity (Kutzner, 2001). Composting occurs in several phases, which are characterized by changes in temperature (Kutzner, 2001):

> Phase 1 (mesophilic phase): A diverse community of bacteria and fungi consumes readily available nutrients, raising the temperature of the compost pile to about 45 °C. During this phase, neither the nutrient supply nor the temperature are important for the community structure, at least where bacteria are concerned.
>
> Phase 2 (thermophilic phase): Thermophilic (high temperature favoring) microorganisms then begin to dominate after a short lag period, changing the community.[14] The temperature increases more as populations of these microorganisms develop. These bacteria and fungi thrive at temperatures starting at about 50 °C, but typically cease activity after 70-80 °C.
>
> Phase 3 (stationary phase): At a certain point, heat production from the activity of microorganisms matches the heat that dissipates from the compost pile, creating a temperature plateau. The composition of the microbial community during this phase remains consistent.
>
> Phase 4 (maturation phase): Surviving mesophilic (medium temperature favoring) microorganisms, or those coming into the pile from outside, succeed the thermophilic bacteria, and the temperature of the pile begins to cool gradually.

Microorganisms need nutrients, water, oxygen, specific temperatures, and a habitat with a suitable pH in order to break down and stabilize waste, creating compost (Kutzner, 2001). The most important nutrients for microorganisms within compost feedstocks are carbon and nitrogen. Ideally, these are found in organic wastes that are not too easily broken down, because they need to support several successive microbial populations. At the same time, the nutrients found within compost become more difficult for microorganisms to obtain, which adds selection pressure. Most

[14] The terms "mesophilic" and "thermophilic" are not based on absolute temperatures, but rather are comparative amongst similar organisms. For example, thermophilic fungi have a lower temperature range than thermophilic bacteria (Kutzner, 2001).

compost feedstocks usually contain an abundance of carbon, which microorganisms use for energy metabolism and biosynthesis of organic molecules. Over time, microorganisms release carbon from the compost pile as carbon dioxide, produced from cellular respiration. On the other hand, nitrogen is in limited supply within compost feedstocks. As the compost moves through different phases, previous populations of microorganisms die, and become the nitrogen source for new ones (along with any remaining nitrogen). Nitrogen can be lost as ammonia (NH_3), so ideally, microorganisms and compost manufacturers keep it fixed in biomass and humic acids, or adsorbed to particles in the compost (Kutzner, 2001).

Microorganisms need water for growth, but too much can hinder aeration of the compost pile (Kutzner, 2001). The total amount of water (measured as a % of dry weight) in compost feedstocks can be in different forms, with different availability. For a given water content, the moisture in some materials is more available than others (*e.g.,* the water in grass clippings is more accessible than the water in saw dust). Water is also produced by microorganisms during aerobic metabolism. Conversely, water is removed from the compost pile through evaporation. As the water content of the compost pile reduces from 50-70% to 30% as it ages, so does the activity of microorganisms. Importantly, the reduction in moisture also encourages the development of different microorganisms, more adapted to dry conditions, such as "xerophilic" fungi (Kutzner, 2001).

While composting is largely an aerobic process, it is not exclusively aerobic (Kutzner, 2001). Compost piles are heterogenous, and even with thorough mixing and aeration, they contain numerous anaerobic "microniches." These are evident from the formation of organic acids that are created through anaerobic process. These acids lead to reductions in the pH of the compost pile. Other processes that produce ammonium (such as the decomposition of proteins) lead to increases in pH. With that said, microorganisms in compost tend to be resilient to a range of pH (Kutzner, 2001).

In most cases, microorganisms colonize compost from the feedstocks themselves (Kutzner, 2001). This includes mesophilic and thermophilic bacteria, as well as fungi. During the composting process, the environmental conditions within the pile select different species that predominate. Some of the bacteria remain present for the entire process, such as many of the mesophilic bacteria species, while populations of others effectively disappear during the thermophilic phase (such as mesophilic actinomycetes and fungi).[15] These then reappear later on when conditions become favorable again. However, estimating populations of microorganisms and their activities within compost can be challenging for a number of reasons. For example, it is common to evaluate them based on spore counts.[16] Spore counts do not necessarily reflect the amount of active mycelium (in the case of fungi) (Kutzner, 2001).

Compost microorganisms are often discussed as three groups (Kutzner, 2001):

- bacteria
- actinomycetes (a specific group of bacteria)
- fungi

During phase 1 of composting, there is a wide mixture of bacteria that develop, and these have no specific species composition (Kutzner, 2001). A few examples of species that might be present at this stage include:

- Gram-positive bacteria
  - *Micrococcus* sp.
  - *Streptococcus* sp.
  - *Lactobacillus* sp.
- Gram-negative bacteria
  - species in the family Enterobacteriaceae
  - species in the family Pseudomonadaceae

During phase 2, thermophilic species of *Bacillus* and *Thermus* begin to dominate. *B. circulans* and *B. stearothermophilus* were extremely common in one study that Kutzner reviewed, representing 87% of colonies that were randomly picked. Other species of bacteria identified included (Kutzner, 2001):

- members of the genus *Streptomyces*
- members of the genus *Thermoactinomyces*

[15] Actinomycetes are a group of filamentous bacteria, whose form is similar at times to that of fungi (Goodfellow, 1994).
[16] In more recent years, microorganism communities in soil and compost are also determined using DNA and RNA methods.

Thermophilic actinomycete bacteria commonly found in composts include (Kutzner, 2001):

- *Saccharomonospora viridis*
- *Streptomyces thermovulgaris*
- *Thermoactinomyces vulgaris*
- *Thermomonospora curvata*

Other actinomycetes that Kutzner (2001) noted in his review (but may be less common) include:

- *Saccharopolyspora rectivirgula*
- *Thermomonospora chromogena*
- *Thermomonospora fusca*
- *Thermomonospora curvata*
- *Saccharomonospora* spp.
- *Thermoactinomyces* spp.
- *Thermocrispum* spp.

Fungi within compost usually belong to one of two classes: the Ascomycetes, or the Deuteromycetes (Kutzner, 2001).[17] However, the actual species involved are numerous and diverse. In some cases, members of the Basidiomycetes also play a role, particularly in later stages of compost maturation. Basidiomycetes are the most typical fungal decomposers of lignin. Fungi are well adapted to soil, compost feedstocks, and compost piles, as they often play a significant role in decomposition of organic matter in nature, degrading a wide variety of materials. Like the bacteria present in compost piles during the mesophilic phase, the species of fungi present initially is determined by what happens to be on or within incoming compost feedstocks. As with bacteria, fungi go through successions as the temperature of the compost pile changes. However, in general, fungi tend to be more heat sensitive than bacteria. Initially, the community of fungi in a compost pile is composed of primary saprophytes.[18] As the pile increases in temperature, the community shifts to thermophilic (or tolerant) fungi. A few examples of fungi found in composts include (Kutzner, 2001):

- *Absidia ramose*
- *Absidia corymbifera*
- *Aspergillus fumigatus*
- *Chaetomium thermophile*
- *Coprinus cinereus*
- *Corynascus thermophilus*
- *Humicola languinosa*
- *Mucor (Rhizomucor) pusillus*
- *Mycelia sterilia*
- *Paecilomyces varioti*
- *Streptomyces* spp.
- *Thermoascus aurantiacus*

<u>How do compostable packaging materials break down?</u>

Ideally, compostable packaging materials break down into carbon dioxide (and or methane), water, mineral salts, and biomass (Ali et al., 2023; R. Liu et al., 2023; Rujnić-Sokele & Pilipović, 2017). These are relatively benign materials in most cases. However, the behavior of compostable materials in the field (soil, water, household and industrial composting systems) is not fully understood (R. Liu et al., 2023). Furthermore, compostable materials may include other additives. For example, polylactic acid-based plastic products can also contain plasticizers (Alhanish & Abu Ghalia, 2021; Y. Wang et al., 2024). Other additives include waterproofing materials like PFAS (Goossen et al., 2023; Schaider et al., 2017b). When a compostable (or other biodegradable) product is broken down, it can release these additives. Because there are a vast number of compostable materials, fillers, plasticizers, antioxidants, stabilizers, and water/grease-proofing PFAS chemicals, we are only able to explore a small number of these substances, and a fraction of the available literature.

[17] Unlike many modern taxonomic groups, the class Deuteromycetes (also known as "fungi imperfecti") is not based on phylogenetics or many of the typical morphological characteristics used in classifying other fungi (Carlile & Watkinson, 1997). Fungi in this class are only found reproducing asexually. While this class of fungi is not a true taxonomic group, it is often used to categorize fungi. A complication to this is that some fungi only reproduce asexually, while other members of the same species reproduce both asexually and sexually. Because of this, a single species of fungus can have two scientific names – one representing the asexual form as a member of the Deuteromycetes, and another as a member of the class Ascomycetes or Basidiomycetes (Carlile & Watkinson, 1997).

[18] Saprophytes or saprotrophs are organisms that feed on dead or weakened organic matter (Carlile & Watkinson, 1997). They are not parasitic; rather, they serve as decomposers. Primary decomposers (or primary saprophytes) are the first organisms to begin breaking down organic matter, typically in an environment with minimal competition. These are followed by secondary and tertiary decomposers, who typically exist in more complex environments.

Many compostable materials are aliphatic polymers. Aliphatic compounds are often linear chains, typically containing single bonds (saturated). Aromatic compounds on the other hand often contain planar rings and are more common in noncompostable plastics. Biodegradation of aliphatic polyesters begins with the hydrolysis of ester bonds (bonds involving the hydroxyl group of an acid), creating smaller, water soluble products (Wu et al., 2016). Biodegradation of polymers also involves abiotic factors such as weathering (Ali et al., 2023). Wu et al. (2016) describes the biodegradation of aliphatic polyesters as having three steps:

1) Biodeterioration, during which time microorganisms adhere to the polymer.
2) Biofragmentation, where polymers are broken down into small water-soluble fragments by extracellular enzymes.
3) Assimilation, where microorganisms take in the small molecules and further process them until they produce carbon dioxide (CO_2), water, and biomass.

The ability for a product to be completely degraded (and what it degrades into) depends on various factors, including temperature and the availability of oxygen (Ali et al., 2023). For example, in aquatic environments, polylactic acid behaves similarly to conventional petroleum plastics.[19] Ultraviolet light can change polymers, creating materials that are both more brittle, but also more resistant to biodegradation (Ali et al., 2023; Wright & Kelly, 2017).

Microplastic contamination (such as that which could be found in food packaging waste) is especially relevant to organic farming, because research has shown that mulching, and organic fertilizers (such as compost) can be a source (Y. Sun et al., 2022). For example, Zhang et al. (2022) performed an 11-year field test using a wheat/maize crop rotation. They found that compost contributed to 47%-75.9% of the total microplastics in the field, including fragments of polyethylene, polypropylene, and polyethylene terephthalate. While none of these would be considered compostable materials, this study highlights the possibility for compost to serve as a pathway for soil contamination.

An additional concern with microplastic contamination is that they have hydrophobic surfaces that adsorb and concentrate different types of contaminants, including (Wright & Kelly, 2017):

- polycyclic aromatic hydrocarbons
- organochlorine pesticides
- polychlorinated biphenyls
- cadmium
- zinc
- nickel
- lead

<u>What is the toxicity of compostable packaging on compost microorganisms, and what are the impacts on microbial diversity?</u>

According to Rujnić-Sokele & Pilipović (2017), unless they are completely broken down, plastics with enhanced biodegradation characteristics have the potential to do more harm in the environment than less biodegradable plastics. However, as noted in the previous section, many bacteria, actinomycetes, and fungi are involved in composting, and the community changes over the composting process. Furthermore, the species present in the composting process are simply those present in or on incoming feedstocks. Therefore, it is both very difficult, and in some cases probably unnecessary to specifically target the toxicity of compostable materials on microorganisms *in compost piles*. Instead, we searched for the effect of compostable packaging materials on microorganisms generally. Where we could, we included studies directly relevant to compost. As there are numerous compostable packaging substances, we selected a number of high-profile biodegradable or compostable packaging substances. According to a recent review, the five dominant biodegradable plastics are (Afshar et al., 2024):

- polylactic acid (PLA)
- polyhydroxyalkanoates (PHA)
- polybutylene succinate (PBS)
- polybutylene adipate terephthalate (PBAT)
- starch blends

Polylactic acid (PLA):

Polylactic acid (PLA) is a biodegradable polyester (Ainali et al., 2022), and can be used for rigid packaging, food service ware, films, fibers, and durable products (J. P. Greene, 2022). However, it needs to reach a certain temperature in order to biodegrade (Rujnić-Sokele & Pilipović, 2017; Y. Wang et al., 2024). Unless it reaches its glass transition temperature (60 °C or 140°F), it does not biodegrade (Rujnić-Sokele & Pilipović, 2017; Suder et al.,

[19] This is especially important because large amounts of plastic are lost to the ocean each year (Wright & Kelly, 2017).

2021). It also requires a moisture rich environment to decompose (Y. Wang et al., 2024). PLA can form polymer fragments (microplastics or nanoplastics) in the environment if not biodegraded fully (Ainali et al., 2022; Y. Wang et al., 2024). Furthermore, in aquatic environments, PLA does not easily break down (Ali et al., 2023).

PLA may contain materials such as plasticizers. In a review, Ali et al. (2023), describes biodegradation studies of PLA combined with the following plasticizers:

- acetyl-tri-*n*-butyl citrate
- a polyglycerol/poly(D-lactide) derivative
- epoxidized linseed oil
- D-limonene
- glucose pentaacetate
- sucrose octaacetate
- glucose hexanoate esters

PLA can also be blended with other polymers to create specific mechanical characteristics, such as (Ali et al., 2023):

- chitosan
- cellulose acetate
- starch
- wood flour
- poly(butylene succinate)
- poly(ß-hydroxybutyrate)
- poly(vinyl acetate)

These materials have different effects on biodegradation. Some materials, like acetyl-tri-*n*-butyl citrate accelerate degradation, while others like epoxidized linseed oil can slow degradation (Ali et al., 2023). We did not have time to explore how these additional substances affected the toxicity of compostable PLA products to microorganisms.

We found two studies related to PLA toxicity to microorganisms. Su et al. (2022) compared the impacts of various microplastics on the marine alga *Chlorella vulgaris*. While they found that all types of microplastics inhibited growth, PLA inhibited growth the most: inhibiting growth by almost 50%. Li et al. (2023) studied the effects of microplastics (including PLA) on *Bacillus amyloliquefaciens*. Like Su et al., they found that microplastics (including PLA) significantly inhibited growth and reproduction of the bacterium. They determined that PLA destroyed the enzymatic antioxidant system, damaging components of the cell wall and disrupted the bacterium's metabolism. Interestingly, the researchers found that PLA microplastics could inhibit some of the negative effects of copper ions (R. Li et al., 2023).

We found several studies describing changes to microbial communities due to exposure to PLA. However, changes in microbial communities with a change in their environment isn't unexpected. Liu et al. (2023) noted that the presence of PLA microplastics can lower soil redox potential, and when PLA microplastics breaks down in soil, they can release acids, leading to decreased soil pH. PLA microplastics also increase the abundance of some fungi and bacteria in soil. Nutrient cycles in soil are closely related to the activity of microorganisms, including the enzymes that they produce. The presence of PLA can stimulate the production of urease and phosphatase enzymes by microbes, and inhibit the activity of fluorescein diacetate hydrolase (these enzymes relate to nutrient metabolism, cell signaling, and microbial activity) (R. Liu et al., 2023).

In an experiment, Liu et al. (2023) found that 0.1% PLA microplastics did not affect shoot biomass of corn. However, at 1%, 5%, and 10%, PLA reduced corn shoot biomass by 32%, 63%, and 69%. Chlorophyll and carotenoid content, as well as root activity decreased with a similar pattern. Soil nitrate (NO_3^-) decreased with increasing concentration of PLA microplastics as well.[20] Liu et al. found that 70% of the total abundance of bacteria in the soil samples were members of the Acidobacteriota, Actinobacteriota (actinomycetes), and Proteobacteria. Addition of PLA increased the abundance of Acidobacteriota, decreased Protobacteria, and did not change the abundance of Actinobacteriota. As we described in the previous section, actinomycetes are bacteria that are important to the composting process.

Liu et al. (2023) also found that fungi in the phylum Ascomycota increased with the addition of PLA, whereas fungi in the order Mortierellales decreased, along with members of the phyla Basidiomycota and Mucormycota. Members of these groups of fungi are often present in compost systems. Liu et al. concluded that PLA microplastics change the community structure of soil microorganisms, over short-term time scales. They also concluded that while PLA

[20] This result is in contrast to what was observed by Seeley et al. (2020) and Wang et al. (2024).

had a positive (increasing) effect on the C:N ratio of soil and plants, it caused a decrease in soil pH, which accounted for much of the effect on corn shoot biomass. The decrease in pH they believed also had an overall negative effect on enzyme activity in the soil, also contributing to the effects on corn plants. They hypothesized that changes in nitrate due to microorganism activity also could have contributed.

Using ribosomal (16S) RNA sequences, Seeley et al. (2020) measured the diversity of bacteria in sediments where polyethylene (PE), polyvinyl chloride (PVC), polyurethane foam (PUF), and polylactic acid were added (PLA). Seeley et al. found that bacterial alpha diversity was highest in sediment with added PLA, and lowest in sediment with PE.[21] Interestingly, the control sediment (no added amendments) had the second lowest diversity. When looking at beta diversity, the authors found that the communities of bacteria present in the control and PLA treatments were similar, also exhibiting minimal changes in diversity over time. The PVC treatment was distinct, while the PE and PUF communities were similar to each other. In the PVC treatment, bacteria in the families Chromatiaceae and Sedimenticolaceae were lower in abundance than in other treatments. “Family XII” bacteria was significantly more abundant in all plastic treatments than in the control.[22] The PVC treatment had higher relative abundance of bacteria in the families Acholeplasmataceae, Anaerolineaceae, Family XII, Izimaplasmataceae, Lachnospiraceae, and Marinilabiliaceae. In contrast with Liu et al. (2023), Seeley et al. found that nitrite (NO_2^-) and nitrate (NO_3^-) production was highest in PUF and PLA treatments. While both experiments indicate that the microbial community structure affects the cycling of nutrients, the two experiments resulted in opposing effects. This is consistent with the conclusions of Wang et al. (2024), who believe that different concentrations of PLA can create different environmental conditions that act essentially as filters for segments of the microbial community.

Very recently, Wang et al. (2024) performed an experiment with compost (cow manure and straw), created intentionally with PLA microplastics. Urea was added to create a C:N ratio of 25:1, and the material was composted for 60-days. The composting process included temperatures exceeding 75 °C (167 °F). The inclusion of PLA into the compost did not have a significant effect on peak compost temperature. Similarly to Seeley et al. (2020), Wang et al. found that including PLA resulted in substantially increased nitrate levels (~30x higher), as compared with the control treatment. This was also associated with an increase in urease activity, and reduced peroxidase activity during the maturation phase. Consistent with other experiments, composts with PLA microplastics also had decreased pH, relative to the control.

Wang et al. (2024) also found that PLA microplastics shifted alpha diversity, with bacteria being more greatly affected than fungi. They believe that PLA microplastics potentially increase microbial competition, which has different effects that depend on the stage of compost production. In the thermophilic phase, composts with PLA had greater decreases in biodiversity than the control compost. The authors note that PLA microplastics release toxic elements such as plasticizers, chlorine, and heavy metals. However, in the final maturation stage, diversity in PLA treatments were higher than the controls. The bacterial community structure of the various treatments differed, and this also changed depending on the composting stage. For example, compared with the control, compost with PLA microplastic had:

- (During the mesophilic phase) higher relative abundance of bacteria in the phylum Firmicutes, while Bacteroidota, Proteobacteria, and Gemmatimonadota decreased.
- (During the late maturation phase) higher relative levels of bacteria in the phyla Actinobacteriota and Firmicutes, but lower relative levels of Bacteroidota, Patescibacteria.

As with Liu et al. (2023), Wang et al. (2024) found that compost with PLA microplastics reduced soil pH, and changed nitrogen cycling in the soil. Likewise, they also found that soils amended with PLA compost produced plants (Chinese cabbage) with significantly reduced biomass and antioxidant capacity. Wang et al. noted that plastic particles have been known to cause oxidative stress, which is consistent with their observation of increased antioxidant enzyme activity within plants.

Polyhydroalkanoate (PHA):

Vicente et al. (2023) and Fernandes et al. (2020) provide excellent review articles describing polyhydroxyalkanoates (PHAs), including microbial substrates, microorganisms known to produce PHAs, and biodegradation. Researchers have identified over 150 different PHA monomers (Z. Li et al., 2016; Vicente et al., 2023). The most well-studied PHA is poly-3-hydroxybutyrate (PHB), which has properties similar to polypropylene (Vicente et al., 2023). PHA can be used to make bottles, bags, containers, and other items (J. P. Greene, 2022).

[21] Alpha diversity refers to “within-habitat” or local diversity, often expressed as species richness. Beta diversity is a comparison between different habitats or ecosystems.

[22] Family XII bacteria refers to an unnamed family of bacteria.

PHA is a natural polyester produced by bacteria (Z. Li et al., 2016; Sudesh, 2013). However, some PHA may be produced using genetically engineered microorganisms (Z. Li et al., 2016; Vicente et al., 2023). PHAs accumulate as granules within bacteria, acting as a carbon and energy storage molecule (Vicente et al., 2023).

PHA can be broken down with hydrolytic enzymes, secreted by various bacteria and fungi (Sudesh, 2013). Researchers consider fungi to have a higher capacity to biodegrade PHA than bacteria (Fernandes et al., 2020). The enzymes break PHA into monomers, which are then further metabolized by microorganisms. PHA is normally water insoluble, but PHA depolymerase enzymes hydrolyze PHA into water soluble forms (Fernandes et al., 2020).

Unlike PLA, PHA will breakdown at normal environmental temperatures in soil (Sudesh, 2013). The ideal temperature for PHA degradation is 28 °C (Volova et al., 2017), substantially lower than those typically found in active compost piles. Above this temperature, PHA breaks down more slowly (Volova et al., 2017). Researchers in one study found that PHA degraded very slowly at 60 °C (Volova et al., 2017). In soils, the time it takes for PHA to degrade by 50% is highly variable, lasting between 16-380 days, depending on a variety of factors (Volova et al., 2017). Also differing from PLA, in some cases, PHA can degrade faster in water than in soil (Volova et al., 2017).

According to Li et al. (2016), PHAs have poor mechanical properties, high production costs, limited function, and are incompatible with thermal processing techniques. It thermally degrades near its melting point, which varies between 40-180 °C, depending on type (EuroPlas, 2024). Therefore, PHAs are modified to enhance their performance, with substances such as (Z. Li et al., 2016; Vicente et al., 2023):

- starch
- cellulose derivatives
- lignin
- PLA
- polycaprolactone
- poly-3-hydroxyvalerate

Bacteria naturally degrade PHAs using two main enzymes: PHA hydrolase, and PHA depolymerase (Vicente et al., 2023). In soil, there is a lag between when PHAs are in contact with soil, and when degradation begins (Volova et al., 2017). This is typical for other compostable materials as well. Microorganisms first have to adhere to PHA products, and adapt their metabolism to produce enzymes before degradation begins (Volova et al., 2017). Degradation can occur in both aerobic and anaerobic environments, but the resulting products differ (Vicente et al., 2023). As with PLA, aerobic degradation of PHA results in the production of carbon dioxide and water, while anaerobic degradation of PHA produces carbon dioxide and methane (Vicente et al., 2023).

Examples of microorganisms that can break down PHAs include members of the following genera (Volova et al., 2017):

- Bacteria
  - *Bacillus*
  - *Pseudomonas*
  - *Streptomyces*
- Fungi
  - *Penicillium*
  - *Absidia*
  - *Gilbertella*
  - *Mucor*
  - *Rhizopus*

Researchers have identified other microorganisms that can break down PHAs as well, including both bacteria and fungi (Volova et al., 2017).

We did not find studies describing that PHAs are toxic to microorganisms. While there are many studies on the biodegradability of PHA, we found few studies that describe their toxicity. They are often referred to as “non-toxic” or “environmentally friendly” (Fernandes et al., 2020; Meereboer et al., 2020) but we did not find studies that explicitly tested the effects of PHAs on microorganisms. However, we did find a study that described the effects of PHA on microbial communities.

In a soil degradation experiment, Volova et al. (2017) found that the composition of the soil microbial community changed considerably after 35 days of exposure to small PHA disks. The dominant species changed, and the quantity of ammonifying and nitrogen fixing bacteria increased 3x. Prototrophic bacteria [those that can produce all of their own nutrients from basic molecules] also increased, by 1.8x, but oligotrophic bacteria [those that normally live in nutrient-poor environments] decreased by 8.3X. Volova et al. hypothesized that the addition of PHA stimulated certain microorganisms, leading to an increase in the rate of soil organic matter transformation. Volova et al. also found that gram-negative bacilli increased, such as *Pseudomonas*, *Stenotrophomonas*, and *Variovorax* spp. Actinobacteria decreased. The researchers did not see any significant changes to fungi.

As the PHA disks were degraded, the bacteria involved produced biofilms (Volova et al., 2017). While some of the bacteria found in the biofilms were primary degraders of PHA (such as *Streptomyces* spp., *Mitsuaria* sp., *Chitinophaga* sp., *Acidovorax* sp., *Roseateles depolymerans*, plus several other species), others were metabolizing monomers or oligomers of PHA liberated by the primary degraders.

Polybutylene succinate (PBS):

Polybutylene succinate (PBS) is produced from either petroleum or biomass-derived succinic acid, and petroleum based 1,4-butanediol (Künkel et al., 2024). These materials are combined in a chemical reaction in the presence of a catalyst (J. P. Greene, 2022).

While PLA is typically rigid, PBS is a flexible material. PBS can be used in a few different applications, including as a liner for paper cups, lids, tableware, and straws (Künkel et al., 2024). It is similar in characteristics to polyethylene terephthalate (PET) (Rafiqah et al., 2021). It can also be used to make sheets, film, bottles, and molded products (J. P. Greene, 2022). PBS has a melting temperature of 115 °C (239 °F), and is easy to process (Rafiqah et al., 2021; Zhao et al., 2005). Because it is expensive, it may be blended with other materials, such as oil palm fiber or tapioca starch (Rafiqah et al., 2021).

The degree to which PBS degrades in soil is variable. Hoshino et al. (2001) placed samples of numerous plastics (including PBS) in soil at 19 different locations in Japan and observed how they degraded over the course of 12 months. Two of the sites were greenhouses, and PBS degraded completely there in 9 months. In contrast, PBS placed in soil at two other sites experienced almost no degradation. On average, PBS samples at the 19 locations decreased in weight by 34% after 12 months. Hoshino et al. did not explore how these plastics affected the microbial communities. Compared with other plastics, PBS degraded more slowly on average than PHB (a type of polyhydroxyalkanoate or PHA), but more quickly than polylactic acid (PLA).

Barletta et al. (2022) consider PBS to not be compostable in a home environment. Additionally, like PLA, PBS has extremely limited biodegradability in marine and aquatic environments (Barletta et al., 2022).

Similar to other biodegradable plastics, PBS is initially slow to biodegrade (Zhao et al., 2005). In a biodegradation study using compost mixed with different forms of PBS (powder, film, and granules), Zhao et al. found that for the first several days, biodegradation was slow. Once biodegradation processes increased, the different PBS material forms decomposed at different rates. After 90 days, PBS powder was 71.9% degraded, while film was only 60.7% degraded. Granules were very resistant to degradation, likely due to their large volume and small surface area. After 90 days, granules were only 14.1% degraded. The researchers identified four microorganisms from the compost that were able to degrade PBS, and tested their response to different concentrations from 0.1% to 0.6% PBS (Zhao et al., 2005):

- *Aspergillus versicolor* (best growth and assimilation of PBS, even at high concentrations)
- *Penicillium* sp. (moderate growth at low concentrations of PBS, low to no growth at higher concentration)
- *Bacillus* sp. (moderate growth at low concentrations of PBS, low to no growth at higher concentration)
- *Thermopolyspora* sp. (low or no growth rate in all concentrations, poor assimilation of PBS)

According to Rafiqah et al. (2021), PBS *may* not be toxic to the environment, and is degraded by the action of the fungus *Fusarium solani*, as well as 39 strains of bacteria in the Firmicutes and Proteobacteria classes.[23] Barletta et al. (2022) noted in their review that unpurified enzymes produced by the fungus *Rhizopus oryzaecultures* decomposed PBS.

[23] *Fusarium solani* can be both a plant and human pathogen.

Wu et al. (2016) conducted an experiment to identify what PBS breaks down into, and how it affected mung bean germination and growth. In order to collect the decomposition products, the researchers resorted to using microorganisms found in compost to degrade PBS film in an artificial, lab environment. The microorganisms used included members of the following genera:

- *Aspergillus* (fungus)
- *Bacillus* (bacterium)
- *Penicillium* (fungus)
- *Thermopolyspora* (bacteria)

After the PBS film was incubated with microorganisms for 10 weeks, the surface of the PBS film changed from smooth to cracked, and with many large holes (Wu et al., 2016). The researchers found fungal mycelia tightly adhered to the PBS film, which they speculated were members of the *Aspergillus* genus. The PBS film exposed to microorganisms had lost about 20% of its weight due to biotic degradation. However, the molecular weight of the PBS film polymers decreased at a greater rate: from an average of 60,462 Da to 22,206 Da (This indicates that while 20% of the PBS had been removed from the film, the remaining material was in the process of breaking down into smaller polymeric pieces.).[24]

Wu et al. (2016) found that as PBS film degraded, it acidified the medium. In the medium with PBS exposed to microorganisms, the pH decreased from 7.2 to 5.2 in the first two weeks. However, at 8 weeks, the pH rebounded to neutral as PBS degraded further. The authors hypothesized that this was due to microorganisms assimilating the acid products as carbon sources.

The microorganisms broke the PBS polymer down initially into water soluble oligomers, and even to their original monomeric units of 1,4-butanediol (B) and succinic acid (S) (Wu et al., 2016). The researchers identified oligomers, created from different combinations of the original monomeric units, such as BS, BSB, SBS, BSBS, BSBSB, and SBSBS. Mung beans were germinated in solutions with these substances and compared with a control medium. The treatment solutions were made from decomposition products recovered at different times (2 weeks and 10 weeks). Wu et al. found that mung beans normally germinated with long sprouts. Mung beans in the treatment with 2-week-old water soluble PBS decomposition products (which were acidic) had shorter sprouts, and some even failed to germinate. However, mung beans treated with water soluble PBS decomposition products recovered in week 10 had improved germination compared with the 2-week treatment. The 10-week-old treatment still did not have as much germination as the control. The authors then performed an additional treatment, by neutralizing the 2-week-old solution with sodium hydroxide. The mung beans treated with this solution performed similarly to the week 10 treatment, indicating that the pH of the solution had a greater effect on germination than the water-soluble PBS products themselves.

Sun et al. (2022) compared microplastics of two conventional and two biodegradable types, and their effect on soil ecosystems:

- polyethylene (PE), a conventional plastic
- polystyrene (PS), a conventional plastic
- polybutylene succinate (PBS), a biodegradable plastic
- polylactic acid (PLA), a biodegradable plastic

The researchers gathered soil from an agricultural field station in Beijing, China (Y. Sun et al., 2022). They mixed soil with microplastics at a rate of 1% by weight. They noted that previous studies indicated that microplastics in some environments could be as high as 7%, so the 1% used in the study was considered a "environmentally relevant." The soil/plastic mixture was kept at 25 °C, and at a humidity of 40%. The resulting mixture was analyzed 5 times, on days 3, 7, 15, 20, and 60.

The researchers found that biodegradable microplastics significantly increased the amount of dissolved organic carbon in soil, as compared with the conventional plastics and the control, where no plastic was included (Y. Sun et al., 2022). The highest dissolved organic carbon was found in PBS treatments. However, the authors noted that other studies have produced different results, with conventional plastics also causing increases in the dissolved organic carbon content of soils, depending on soil type, microplastic type and concentration, and exposure duration.

[24] 1 Da (Dalton) is equivalent to 1 atomic mass units, or *amu*.

In all treatments, the following groups of bacteria were dominant (Y. Sun et al., 2022):

- Actinobacteria
- Proteobacteria
- Chloroflexi
- Acidobacteria
- Firmicutes

Generally, the effect of microplastics was to decrease the relative abundance of Actinobacteria (control 29.9%, 13.4% PBS treatment), and increase the levels of Proteobacteria (control 24.9%, 40.7% PBS treatment) (Y. Sun et al., 2022). Microplastics of all types also increased the relative abundance of bacteria in the Firmicutes. Microplastics also decreased the relative abundance of aerobic and gram-positive bacteria, while increasing the abundance of anaerobic and gram-negative bacteria.[25] PBS and PLA treatments increased the abundance of Alphaproteobacteria and Gammaproteobacteria. PBS treatments depleted the number of Actinobacteria, Chlorflexi, Gemmatimonadetes, Nitrospirae, and Acidobacteria. The authors also found that the conventional plastics treatments lead to communities with fewer keystone bacterial species, compared with the biodegradable plastics.

Compared with conventional plastics, the biodegradable microplastic treatments caused greater community turnovers (Y. Sun et al., 2022). In other words, there was greater dissimilarity between successive communities in the PBS treatments, indicating a greater environmental disturbance.

The researchers also evaluated the functional traits (ecological role) of microorganisms in the soil ecosystem (Y. Sun et al., 2022). However, the authors acknowledged that the rRNA methods that they used to evaluate functional traits had limitations, and these make their findings incomplete.[26] With that said, the two must abundant functional traits according to the researchers were:

- chemoheterotrophy[27]
- aerobic chemoheterotrophy

Microplastics (both conventional and biodegradable) decreased the relative abundance of these functional traits over time, as well as other traits such as (Y. Sun et al., 2022):

- degradation of aromatic compound functional groups
- ligninolysis (decreased breakdown of lignin)
- aromatic hydrocarbon degradation
- phototrophy (decrease in photosynthesis by bacteria)

Consistent on other studies with PLA [such as Seeley et al. (2020); Liu et al. (2023); Wang et al. (2024)] , PBS and PLA altered (in this case, enhanced) the relative abundance of nitrogen and sulfur cycling functional traits, including (Y. Sun et al., 2022):

- nitrogen fixation
- nitrate respiration
- nitrogen respiration
- sulfur respiration
- sulfate respiration
- thiosulfate respiration

Sun et al. (2022) found evidence that more than other plastics, PBS may have induced horizontal gene transfer in microorganisms. However, the authors provided very limited discussion of this topic.

Polybutylene adipate terephthalate (PBAT):

Polybutylene adipate terephthalate (PBAT) can be used for the production of (Ghasemlou et al., 2024; Jian et al., 2020):

- stretch cling films for overwrapping fresh produce
- shopping bags
- mulch films
- single-use utensils

[25] It is well known in plant pathology that most bacterial plant pathogens are gram negative (Saddler, 2001).
[26] One of the major limitations of rRNA methods for identifying the species in a soil sample is the limited number of genetic sequences that are catalogued compared to the total number of microorganisms that exist. However, other methods have limitations as well.
[27] Chemoheterotrophy is the process of utilizing carbon fixed by other organisms (photosynthesizers, primarily) or other sources such as minerals.

PBAT is fully petroleum-based and the copolymerization product of adipic acid, 1,4-butanediol, and aromatic terephthalic acid monomers (Ghasemlou et al., 2024). Manufacturers may blend PBAT with other polymers (*e.g.,* PLA) or reinforce it with nonorganic (*e.g.,* talc and kaolin) or organic materials (*e.g.,* starch and lignocellulose) (Itabana et al., 2024). Some of these reinforcement materials may serve dual purposes, as both filler material and plasticizer.

These reinforcement materials and associated additives (*e.g.,* maleic anhydride) required to combine them have different effects on biodegradation (Anunciado et al., 2021; Itabana et al., 2024). We did not have time to explore how these additional substances may affect terrestrial microbial communities, or any potential microbial toxicity of compostable PBAT products.

There are two ways that PBAT typically undergoes biodegradation in the soil or in compost piles (Itabana et al., 2024; T.-Y. Liu et al., 2023). One way this process occurs is non-enzymatically, this may involve thermal decomposition and hydrolysis of polymer chains. The other way this process occurs involves the enzymatic degradation by bacteria and fungi (Itabana et al., 2024; T.-Y. Liu et al., 2023). PBAT is compostable in the sense that polyesters are susceptible to enzymatic degradation by esterase (Martínez et al., 2024; Mörtl et al., 2024). The biodegradation products of PBAT include (Martínez et al., 2024):

- 1,4-butanediol (BDO)
- adipic acid (AA)
- terephthalic acid (TPA)
- terephthalic acid-butanediol-terephthalic acid (TBT)
- terephthalic acid-butanediol-terephthalic acid-butanediolterephthalic acid (TBTBT)

Scientists found that experimental studies on PBAT degradation in the open environment are limited compared to PHA and starch blend bioplastics (Afshar et al., 2024). However, we did find some information. For example, Muroi et al. (2016) measured changes in the weights of PBAT films incubated in the soil at 30 °C. The weights of these PBAT films gradually decreased with time, and weight loss reached 1.81 mg/cm^2 (approximately 22% the initial weight of the film) after six months. Scientists also demonstrated that the incorporation of hydrophilic polymers and lignocellulosic fillers into PBAT can speed up its degradation in soil (Itabana et al., 2024).

Muroi et al. (2016) also observed significant changes within the soil fungal community of both PBAT mulch film and soil exposed to that mulch film. The scientists observed that fungi belonging to the phylum Ascomycota colonized the surface of the mulch film. They also found seven plant pathogens of fungal origin in the soil samples. Notably, *S. terrestris* (an onion pathogen) abundance increased on both the mulch film and the soil sample collected in the nearby vicinity, compared to the control soil sample. The scientists did not observe a significant change in the bacterial community of either PBAT mulch film or soil exposed to that mulch film (Muroi et al., 2016).

In a study similar in nature to that of Muroi et al. (2016), Liu et al. (2022) observed a comprehensive decrease in bacterial diversity and significant changes within the soil bacteria community composition of soil exposed to PBAT mulch film. The scientists observed increased populations of the dominant compost phyla, most notably Actinobacteriota (27.6%) and Proteobacteria (23.5%) and inhibition of minor phyla, Acidobacteriota, Gemmatimonadota and Myxococcota. The Acidobacteriota population decreased the most at 42.1% (L. Liu et al., 2022).

Another study, by Mörtl et al. (2024), looked at the industrial-scale composting of bioplastic carrier bags composed of 20% starch, 10% additives, and 70% PBAT. The scientists observed that the matured one-year-old compost sample did not contain sugars, indicating the successful degradation of starch present in the biopolymer and that of other complex carbohydrates from the manure. However, scientists still detected BDO, AA, and TPA, along with the intermediate products of (4-hydroxybutyl)adipate (AA+), bis(4-hydroxybutyl)adipate (AA++), and (4-hydroxybutyl)terephalate (PTA+). The presence of these products indicates that PBAT did not biodegrade completely (Mörtl et al., 2024).

We found no research pertaining to the microbial toxicity of PBAT or its degradation products in the soil or compost. A computational analysis of the electron transfer capacity conducted by Martínez et al. (2024) concluded that PBAT, TPA, TBT, and TBTBT are the best electron acceptors amongst PBAT and its known biodegradation products. Consequentially, the presence of these compounds in a given environment may theoretically result in the oxidation of biomolecules. The oxidation of biomolecules is associated with the presence of free radicals that can cause damage to organs and tissues (Martínez et al., 2024).

Starch (*e.g.*, thermoplastic starch), starch blends:
Starch blends can be used for the production of (Afshar et al., 2024; Surendren et al., 2022):

- edible coatings
- agricultural mulch films
- food packaging (*e.g.,* films, cushion foam, and trays)
- films and bags
- single-use utensils
- fillers for other biobased and biodegradable plastics

Starch is a common natural polymer composed of amylose and amylopectin (C. Cui et al., 2021). Both amylose and amylopectin consist of glucose monomers. Common sources for this material include the following crops (C. Cui et al., 2021; Surendren et al., 2022):

- cassava
- corn
- potato
- rice

Manufacturers convert starch raw materials to thermoplastic starch blends (TPS) by combining one or more plasticizers with other biobased or biodegradable polymers and passing them through an extruder. An extruder blends materials by exposing the materials to heat and high shear force (Surendren et al., 2022). Common plasticizer materials that manufacturers may combine with starch include glycerol, glycol, and sorbitol (Ghasemlou et al., 2024). We did not have time to explore how these additional substances may affect microbial communities, or any potential microbial toxicity of compostable starch blend products.

Starch by itself degrades relatively easily and an entirely starch film may degrade entirely after 32 days when composted (C. Su et al., 2023). The degradation of starch blend film in compost involves the following process (C. Su et al., 2023):

- water and microbial dispersion on the film
- film component hydrolysis and oxidation; carbon dioxide release
- film component degradation; additional carbon dioxide release
- porous structure and film destruction

Many microorganisms can directly biodegrade starch molecules by producing enzymes. These enzymes cleave the bonds linking the amylose and amylopectin molecules to produce simple sugars that are directly digestible by microorganisms (Ahsan et al., 2023). The biodegradation process of a starch blend film often experiences an initial lag period lasting 2–8 days, then an accelerated degradation stage, and eventually the process plateaus once degradation (total or partial), is complete (C. Su et al., 2023).

Manufacturers typically mix starch with other biopolymers, such as PLA or PBAT to create TPS, and these additions can affect the kinetics of product degradation (Falzarano et al., 2024). Commercial TPS blends can vary in starch content from 20-90% (Van Roijen & Miller, 2022). Scientists found that the degree of biodegradation of TPS blends when composted can range from 22-100% by mass (depending on the composition of TPS). Scientists conducted the majority of these studies under industrial composting conditions (50-60 °C) (Van Roijen & Miller, 2022).

Morro et al. (2016) investigated the biodegradation of starch blend films composed of ethylene-butyl acrylate copolymer (EBA) with different amounts of TPS (10, 30, and 60%). The scientists used glycerol as a plasticizer in the TPS. They exposed these blend films to a mixture of soil microbes (*Bacillus subtilis, Bacillus borstelensis* and *Bacillus licheniformi*) in a bioassay reactor and observed the films over 28 days. The scientists observed the most significant modifications of the film surface in the EBA/60% TPS blend (Morro et al., 2016). They concluded that the degree of degradation observed was related to the concentration of the starch in the blend film (Morro et al., 2016). The exact mechanism connected to this is unclear. However, the scientists hypothesized that in TPS blend materials with lower concentrations of starch, that some interaction with the copolymer and plasticizer may reduce the starch fraction available for microbial degradation (Morro et al., 2016; C. Su et al., 2023).

We found one study specifically describing the effects of bioplastic starch blends on microbial communities in soil. Wickasono et al. (2022) studied the dynamics of the bacterial community found in potting soil (commercial mixture of guano, humus, manure, roasted rice husks, dolomite and cocopeat) for a period of 120 days. The scientists left a portion of the potting soil untreated (negative control) and buried commercial carrier bags (aka retail or shopping bags) composed of cassava starch-based bioplastic in another portion of potting soil. The most dominant bacterial phyla present in the potting soil control samples and the potting soil exposed to the starch blend bioplastic were Proteobacteria, Bacteriodota, Actinobacteria, and Myxococcota. This is similar to microbial succession during cow manure and corn straw composting (Wicaksono et al., 2022). These dominant phyla (and additional minor phyla) remained present in the soil with or without starch blend bioplastic exposure over time, but the community composition also changed over the course of the experiment period in both. Proteobacteria abundance generally increased and by day 120, the population was slightly higher in potting soil exposed to starch blend bioplastic. Actinobacteriota increased slightly in both the negative control and treated potting soil, but by day 90 and 120, the abundance in control soil was relatively higher. In contrast, the Myxococcota population showed a constant decrease throughout the experiment in all potting soil samples. None of these bacteria were abundant continuously, they dominated at specific time points during the experiment period. The scientists concluded that the introduction of the starch blend bioplastic into the potting soil increased not only the population of bacteria known for their ability to directly utilize plastic components for their growth, but also the abundance of those that may interact with direct degraders. Additionally, bacterial groups involved in nitrogen cycling also increased throughout the experiment period (Wicaksono et al., 2022).

We found no research pertaining to microbial toxicity specific to starch blend bioplastics or TPS, in the soil or compost environment.

Per- and polyfluoroalkyl substances (PFAS):

Microbial communities are affected by the presence of PFAS (He et al., 2024). However, research on PFAS' effects on compost microorganisms is limited (He et al., 2024). PFAS are primarily referenced by their acronyms (see *Table 2*). PFAS are resistant to microbial degradation due to their high-energy carbon-fluorine bonds and are toxic to algal cells and bacteria (Goossen et al., 2023; Qiao et al., 2018). Researchers have identified at least four toxicity modes (Nobels et al., 2010):

- oxidative damage (*i.e.*, oxidation and exposure to free radicals)
- DNA damage
- general cell lesions
- membrane damage

Which modes of toxicity are predominant to bacteria (more than one can occur simultaneously) depend on PFAS type, quantity, and the composting stage (He et al., 2024; Nobels et al., 2010). Exposure to PFAS, especially when combined with microplastics, may increase the production of reactive oxidative species, weakening the antioxidant defenses of the cell and causing oxidative stress (Junaid et al., 2024). PFAS can also be incorporated into bacterial membranes, altering them by reducing their cell permeability (Ma et al., 2022). The damage caused by one toxicity mode may influence the activation of another mode (Nobels et al., 2010). For example, PFOA causes oxidative stress, leading to levels of oxide and hydrogen peroxide (O_2^- and H_2O_2) above the defense capacity of the cell, which induces DNA damage (Junaid et al., 2024; Nobels et al., 2010). This reason is why manufacturers also use PFAS in pesticides and herbicides (Khair Biek et al., 2024). PFAS carbon chain length is the main predictor of toxicity and generally increases as chain length increases (Nobels et al., 2010; Qiao et al., 2018).

He et. al (2024) observed microorganism compost trends and hormesis when composts were exposed to PFOA composts.[28] The researchers used rRNA gene sequencing to track the microorganisms and found that *Bacillus* spp. were stimulated between days 5 and 14. Bacteria in the phylum Firmicutes, known for their thermal tolerance and ability to degrade organic material, decreased in abundance after day 14. Specifically:

- *Tuberibacillus*, *Aeribacillus*, *Geobacillus*, and *Caldibacillus* were inhibited.
- Bacteroidota became the dominant phyla after day 14 by being more tolerant of PFOA.
- *Sphingobacterium*, *Myroides*, *Sphingobacteriaceae*, and *Taibaiella* increased.

The researchers attributed these results to PFOA inhibiting certain genes responsible for glycolysis, the glucose-to-energy breakdown process necessary for carbohydrate metabolism. In composts, this can be seen in the primary fermentation stage, when organic compounds, including carbohydrates, are broken down (Khair Biek et al., 2024). The process requires an abundant amount of oxygen. The remaining decayable organic matter is converted into nitrogen, sulfur, phosphorus, and other inorganic compounds during composting, which, together with stabilized organic matter, form humic substances (compost) in the later stages (Khair Biek et al., 2024). Quinones are a class of compounds that form in the early stages of composting and, because of their instability, later combine with amino acids and peptides to create humic substances (J. Wang et al., 2024). Bacterial quinone groups are an important component for humic substance formation (He et al., 2024).

[28] Hormesis: an adaptive response to moderate stress where a system improves its functionality and/or tolerance to more severe stressors (Calabrese & Mattson, 2017).

He et. al (2024) observed that glycolysis gene inhibition in the early composting stages began a cascading energy synthesis inhibition effect in the thermophilic stage. PFAS suppressed carbon metabolism in bacteria in the initial phases of composting. The suppressed carbon metabolism decreases the rate of humification by lowering quinone availability. In the early composting stages, pressure from the toxicity of PFAS selected for specific microbial genes and pathways. This selection pressure reshaped the compost microbial community, leading to an assemblage of species that moderated the amount of reactive oxygen species present. The researchers concluded that because reactive oxygen species levels decreased in the maturation stage, the microbial communities adapted to PFOA through hormesis. Though the compost microbial community adapted to PFOA's effects, the process took time and, by the later composting stages, there was a reduced supply of quinone and therefore a reduced humic substance quantity in the finished compost (He et al., 2024).

Plasticizers:
Plastic products (including compostable packaging) often contain additives such as plasticizers, fillers and colors. Many different materials are used as plasticizers, in different chemical categories. Based on a survey of plastics industry websites, some plasticizers bond directly to the plastic polymer (serving as a copolymer), while others do not chemically bond with the polymer. There are sometimes referred to as "internal" plasticizers and "external" plasticizers, respectively.

Plasticizers are non-volatile organic compounds that make plastics more flexible, more fracture resistant, and easier to process (Alhanish & Abu Ghalia, 2021). There are a variety of plasticizers, but petroleum phthalate plasticizers are most common (a type of external plasticizer). These plasticizers can be harmful to human health as well as the environment. In some cases, these may be blended with nanoparticles in order to further modify their properties. Researchers have developed bio-based plasticizers that are now replacing older, "synthetic" plasticizers, such as phthalates. Examples of bio-based sources include (Alhanish & Abu Ghalia, 2021):

- diester succinates
- tung oil
- levulinic acid
- eugenol-levulinic acid
- tartaric acid
- glycerol-adipic acid
- 2,5-bis(hydroxymethyl furan) derived from plants
- 5-hydroxymethyl-2-furancarboxylic acid
- castor oil
- tributyl citrate/propargyl ether tributyl citrate/oleic acid/poly(dimethylsiloxane) diglycidyl ether terminated

According to Alhanish & Abu Ghalia (2021), biodegradability and toxicological data on many plasticizers is limited. Due to limitations in time, we did not pursue literature on these materials further, but we recognize that understanding the toxicology of these and other additives are an important part of the overall picture.

<u>Focus Question #4: Describe any research that shows a relationship between use of compostables, and consumer behavior related to single use plastic products. *E.g.*, is there information indicating whether the availability of compostable plastics may increase, decrease, or not affect consumers' decision to use a single use item?</u>
Scholarly research into compostables and consumer behavior is relatively recent and fragmented. Since roughly 2008, researchers have studied classes of food packaging products that are labeled as "environmentally friendly" or "sustainable" as opposed to particular materials or characteristics (Ketelsen et al., 2020). Studies of consumer behavior measure the willingness or likelihood of consumers to purchase items for perceived environmental benefit, or consumers' understanding of those benefits (Footprint, 2022). They do not investigate the relationship between that behavior and the availability of any particular type of product.

Moreover, researchers rarely use actual products or photos of products. (Ketelsen et al., 2020; Ruf et al., 2022). In a review of 46 journal articles by Ketelsen et al., (2020), only four articles describe experiments. Authors of several literature reviews noted a need for investigations into how consumers respond to specific purchasing situations and products, with emphasis on measured behavior rather than values- or preference-based hypothetical questions (Allison et al., 2021; Ketelsen et al., 2020; Ruf et al., 2022). Nemat et al. (2020) suggested that researchers should study how appearance characteristics such as shape, texture, and color, might improve consumers' ability to sort waste accurately. How packages are designed and how manufacturers label products significantly affect consumers' recognition of compostable items, both when they are purchased, and when they are disposed of (Allison et al., 2021; Composting Consortium & BPI, 2023). According to Ketelsen et al., consumers rely on specific design elements such as color and images of nature, which also exposes a need to regulate against deceptive labeling and design (2020).

Researchers have documented a number of barriers to consumers' ability to choose and dispose of compostable plastics correctly. For example, consumers exhibit confusion regarding the different terms and labels that appear on compostable plastics, including "biodegradable," and "made from plants," (Allison et al., 2021; Ketelsen et al., 2020; Ruf et al., 2022). When consumers become confused around label terms, they develop skepticism and mistrust. Allison et al. (2021) found that people who were home and community composters resisted buying compostables. This group believed that compostables do not compost effectively and are difficult to distinguish from non-compostable items. The researchers also found that consumers were generally skeptical of manufacturers' and retailers' claims regarding biodegradation and environmental benefits. According to EPA research, members of the public are also concerned that compostable products could have more environmental and human health impacts than conventional single use plastics (2024a).

Consumers also may be confused about what is compostable; between 30% and 50% of survey respondents said an item labeled "made from plants" could be composted (Composting Consortium & BPI, 2023). In addition, consumers lack access to composting services, as infrastructure is generally underdeveloped, which may also be a factor in consumer decisions (US EPA et al., 2024) (see *How are they identified or labeled?*, *above*). In many places, a consumer can choose and use a compostable item without understanding that they cannot dispose of it as the manufacturer intended. In a 2019 Australian survey, 62% of respondents said they would place bioplastics in the recycling bin (Van Roijen & Miller, 2022). In 2022, 28% of American survey respondents said they would dispose of their compostable packaging with the recyclables (Composting Consortium & BPI, 2023). The same survey showed that consumers with access to compostables collection do not necessarily dispose of items more appropriately despite having more options (Composting Consortium & BPI, 2023). Babka (2019) also points out that the Resin Identification Codes with the "chasing arrows" sign appears on many items and misleads consumers to believe an item is recyclable. It is clear from research that consumers are aware of the problems of plastic. In a survey of 5,000 American and European adults, 72% said they regularly avoided single use plastic items, and a similar percentage go out of their way to avoid using single use plastics for takeout and groceries (Footprint, 2022). Ketelsen et al. mention several studies showing participants' preference for reduced packaging, or unwillingness to buy items with excessive packaging (2020). However, the wide range of environmental benefits and drawbacks, with unclear labeling and messaging, along with inconsistent waste collection infrastructure and regulation, are barriers to the adoption of compostable plastics. They also make consumer buying decisions more complex and also more difficult for researchers to analyze.

Authors investigating how to reduce single use plastics discuss compostables as one part of a complex solution or strategy, often grouped with recyclables, bio-based products, or biodegradable plastics (Arijeniwa et al., 2024; Rabiu & Jaeger-Erben, 2024; State of Oregon DEQ, 2019). For example, Rabiu and Jaeger-Erben suggest two elements are key to reducing single use plastics: the need to transform everyday social practices towards lower plastic consumption, and availability of viable alternatives (in which they count compostable plastics) (2024). In a report on consumer recycling behavior, results from surveys and pilot studies indicate that investment and outreach can stimulate behavior change, but availability of a particular product type might be a small part of the program (The Recycling Partnership, 2023). In interviews conducted by Springle et al. (2022), stakeholders expressed a concern that bioplastic food packaging could prolong reliance on single use items and displace investment in cyclical reuse systems. Researchers differ on whether to count compostable plastics as "single use plastics." But they do not present data on how use or availability of compostable plastics affect consumers' selections of single use items. Also lacking is comprehensive data on how consumers dispose of compostables (Hermann et al., 2011). Some states may report facilities' permitted composting capacity, but not collect data on actual composted food quantity (Goldstein, 2018). In addition, most facilities (66% of respondents in a 2018 survey) are privately owned and do not share such data (Goldstein, 2018).

Focus Question #5: How frequently are individual ASTM standards such as D6400, D6868 and D8410 updated? How are these updates made?

Revisions to ASTM standards may be proposed at any time for consideration by the responsible ASTM subcommittee (ASTM International, 2023). ASTM includes both main committees and subcommittees:

- The main committee for ASTM D6400 and D6868 is Committee D20 on Plastics.
  - The responsible subcommittee for ASTM D6400 and D6868 is Subcommittee D20.96 on Environmentally Degradable Plastics and Biobased Products.
- The main committee for ASTM D8410 is Committee D10 on Packaging.
  - The responsible subcommittee for ASTM D8410 is Subcommittee D10.19 on Sustainability and Recycling.

Subcommittees review standards in their entirety within five years of the last approval date (ASTM International, 2023). The review process is very complicated, and requires a ballot for reapproval, revision, or withdrawal.

- The subcommittee approves a motion to reapprove, revise, or withdraw a standard for issuance to a main committee ballot.
- Any negative vote from the main committee must be considered by the recommending subcommittee.
- A negative voter may withdraw the negative vote at any time, or the subcommittee can determine a negative vote to be unpersuasive, in which case the issue is passed back to the main committee.
- Acceptance of the subcommittee recommendation by the main committee requires at least two-thirds affirmative majority vote.

If the responsible subcommittee has not reapproved the standard by December 31 of the eighth year since the last approval date, the standard is withdrawn (unless there are unresolved negative votes from the main committee). An unresolved negative vote from the main committee is one without a withdrawal or without an unpersuasive motion from the responsible subcommittee. Without resolution of the negative votes by the main committee, the standard is withdrawn.

The final two digits of the standard identifier, following the dash (for example, D6868-21) indicate the year of revision. If the number following the dash is followed by "R" and two more digits or contains a four-digit year in parentheses, for example D5338-15R21 or D5338-15(2021), this indicates that the standard was reapproved without revisions. All previous versions are available for purchase, indicating the frequency of approval and revision. ASTM D6400 was first published in 1999, and was revised in 2004, 2012, 2019, 2022, and 2023, indicating an increased rate of revisions in recent years. ASTM D6868 was published in 2003 and revised in 2011, 2017, and 2019. ASTM D8410 was published in 2021 and revised in 2022. ASTM D5338 was first published in 1998, reapproved in 2001 and 2003, revised in 2011 and 2015, and reapproved in 2021.

Focus Question #6: Is there any research comparing the quality and soil benefits of municipal compost (*i.e.*, typically containing compostable materials) with on-farm compost (*i.e.*, typically not containing compostable materials)?

Composting nationwide uses diverse materials and methods, and serves numerous end-uses (Sikora & Sullivan, 2000). Municipal compost refers to compost made from organic waste materials collected by municipalities and processed as part of their solid waste management programs. This is one type of composting, but government entities or private enterprises can run composting programs on a regional scale as well as locally. In many instances farmers also compost locally on their operations (US EPA, 2025). Municipal composters primarily compost yard waste, followed by food waste, and may also process biosolids. These and other industrial compost operations are large-scale. They typically market their products for off-site use and must comply with regulatory requirements.

On-farm composters more commonly compost manure, animal mortalities, and crop residues (Sikora & Sullivan, 2000). On-farm composting is typically smaller scale, employs low-technology methods, more often utilizes the compost product on-site, and has more limited regulatory oversight (Sikora & Sullivan, 2000). However, some on-farm compost operations run by large-scale dairies, feedlots, or poultry producers function on a scale more similar to industrial composting operations (Sikora & Sullivan, 2000).

Municipal compost products and composts produced on-site at different farm operations vary in their composition, appearance, and function. Due to this, it is difficult for authors to draw broad comparisons through individual research projects or literature reviews, which often focus on specific aspects of composting. We found one study that directly compared the quality and soil benefits of municipal compost with on-farm compost; however, the authors did not state whether the municipal compost was made using compostable feedstock materials. Municipal composts, while more likely to contain food waste as a feedstock, do not necessarily contain compostable products. We discuss this study immediately below. Later, we approach this question in a different way.

Italian study of municipal vs. on-farm compost

One study in Italy compared quality characteristics of a municipal compost with those of an on-farm compost, and their effects on intensively-farmed soil (Scotti et al., 2016). The researchers used on-farm compost made from corn, lettuce, and starter compost that had been composted in static aerated piles over 45 days plus 2 months of curing. Scotti et al. provided limited information on the municipal compost identity, simply noting that it was a commercial compost from the organic fraction of solid municipal waste.

The C:N of the on-farm compost was 17.1:1 compared to 13.3:1 for the municipal compost. The on-farm compost had higher levels of organic carbon (476 g C/kg vs. 260 g C/kg for the municipal compost) and more stable, recalcitrant carbon (resistant to degradation) than the municipal compost. The on-farm compost also had more total nitrogen (28 g total N/kg or 2.8% vs. 20 g total N/kg or 2.0% for municipal compost).

The municipal compost had higher levels of heavy metals and sodium than the on-farm compost, possibly due to contaminants and salt in food waste feedstocks. To account for the different nitrogen loads, the researchers applied the two composts at slightly different rates (6.0 Mg DM ha^{-1} for on-farm and 8.5 Mg DM ha^{-1} for municipal compost) to intensively farmed greenhouse soils. They then sampled the soils after 1, 4, 8, 12 and 15 months.

After one year, soils treated with each of the composts showed increased organic carbon content (+25% for on-farm compost and +36% for municipal compost), nitrogen content (+40% and +60%, respectively), electrical conductivity and exchangeable sodium (19% and 25%, respectively) compared to untreated controls. Only the soils treated with on-farm compost, however, showed an increase in available phosphorus (+36%) compared to controls. Neither of the compost treatments significantly affected other parameters such as pH, cation exchange capacity, exchangeable calcium, magnesium and potassium ion concentrations. The scientists also measured enzymatic indicators and found that both treatments stimulated microbial activity. However, the result was not uniform among all enzymatic indicators measured due to the different nature of carbon compounds in the two types of compost. The authors concluded that on-farm compost would be a viable alternative to municipal compost for amending agricultural soils, and would cause less of an increase in soil salinity than municipal compost (Scotti et al., 2016).

<u>Alternative approach to the question</u>
In the absence of additional direct research, another way to investigate the quality and soil benefits of municipal compost with that of on-farm compost, is to break the question down into discrete pieces and address them individually.

- How likely is municipal compost to contain compostable products?
- How is compost quality measured?
- What factors influence compost quality?
- What are the soil benefits of applying compost?
- What research is available on the quality and soil benefits of composts containing compostable materials?

How likely is municipal compost to contain compostable products?
Many commercial compost facilities still view compostable products as contaminants and reject them.

An investigation of 92 commercial composting facilities operating in California found that only 34 accepted food waste (Babka, 2019). Of those 34, only 14 accepted compostable plastics. Others remove compostable plastics from feedstocks prior to composting. Commercial composting facilities that do accept compostable plastics each have their own program for identifying and receiving only specific kinds of compostable plastic products. Babka did not report on whether the facilities accepted paper-based compostable products.

A separate survey four years later by CalRecycle (2023) identified the same number of composting facilities in California that accepted foodwaste (34). Twenty-four of these facility operators responded to a survey. Twenty of them said they accept uncoated paper and fiber products, but do not accept plastic-containing materials. The four that do only accept plastic bags claimed to be compostable, but not any other plastic-containing materials (CalRecycle, 2023). This finding indicates that 10 fewer facilities in California accepted compostable plastics in 2023 than four years prior, notwithstanding California's efforts to divert more organic matter away from landfills through mandated composting requirements (State of California, 2021).

In a broad survey of commercial composting facilities nation-wide, researchers reported on 185 municipal composting facilities that accept food-waste (Goldstein & Coker, 2021). Representatives from 103 of these facilities responded to the survey:

- 61 reported that they accept compostable paper products.
- 49 reported that they accept certified compostable plastic.

Facilities gave the following reasons for not accepting compostable packaging (Goldstein et al., 2023b):

- Contamination from single-use plastic packaging and film plastic bags (78% of 55 respondents)
- Compostable bioplastics not disintegrating in the composting process (58% of respondents)
- Compost is sold to certified organic growers (50% of respondents)
- Insufficient product labeling to ensure certified compostable packaging (49% of respondents)
- Potential PFAS contamination from molded fiber products (47% of respondents)

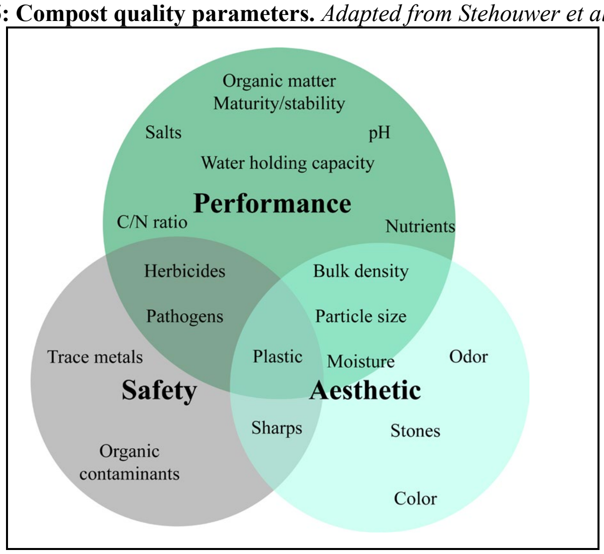
The potential for contamination of compost by non-compostable materials or unwanted feedstocks is a major challenge that impacts the extent to which composting facilities will accept compostable products as feedstocks (CalRecycle, 2023). Municipal and other industrial composters can prevent contamination by collecting already-separated organic wastes (source separated by the consumer) for their composting systems. Source separation is more effective at preventing compost contamination than the composter mechanically separating feedstocks at the composting facility (Gong et al., 2024; Wei et al., 2017; J. Zhang, Ren, et al., 2022). Non-source separated collection generally contains higher levels of contaminants such as heavy metals (Bernal et al., 2017; Wei et al., 2017). However, not all consumers separate their waste.

Identifying what is and isn't a compostable product presents a challenge both to consumers and commercial compost facilities alike. One researcher in Poland described inconsistent and unclear labeling on compostable product packaging as one barrier to effective composting (Raźniewska, 2022). They noted that variations in labeling may have contributed to improper sorting and disposal of compostable products. The author suggested that anonymity, difficulty in identifying compostable packaging, not having the infrastructure of receptacles to receive compostable waste, and resistance to change all challenge the development of circular waste management for compostable packaging. They concluded that consumer awareness and behavior, infrastructure, and compostable packaging that composts effectively all need to grow up together in order for the system to work as a closed loop (Raźniewska, 2022).

How is compost quality measured?

Compost quality is not a single attribute, but a compendium of desirable attributes for a given purpose, site, and or crop (Bernal et al., 2017; Sullivan & Miller, 2001). There are therefore many ways to measure compost quality. Stehouwer et al. (2022) group compost quality parameters by performance, safety, and appearance, noting the overlap between these areas (see *Figure 5*).

Figure 5: Compost quality parameters. *Adapted from Stehouwer et al. (2022).*



Different members of the composting industry may focus on certain compost features more than others. For example, commercial composters in California need to focus on the safety of their compost for the environment and end users due to state regulations that limit physical contaminants, pathogens, and metals concentrations (see *Table 6*). These regulations, although focused on safety, address only a fraction of the potential contaminants that compost can transfer to soil (Brändli et al., 2005).

Table 6: California state quality standards for land-applied commercial compost

Regulatory citation	Quality standard
14 CCR § 17852(a)(24.5) Land Application	Compost applied to land, including land zoned only for agricultural use, may contain no more than 0.5% by dry weight of physical contaminants greater than 4 mm (no more than 20% by dry weight of this 0.5% may be film plastic greater than 4 mm)
14 CCR § 17868.2 Maximum Metal Concentrations	AS, 41 mg/kg Cd, 39 mg/kg Cr [29] Cu, 15000 mg/kg Pb, 300 mg/kg Hg, 17 mg/kg Ni, 420 mg/kg Se, 100 mg/kg Zn, 2800 mg/kg
14 CCR § 17868.3(b) Pathogen Reduction	Fecal coliform, less than 1,000 MPN/g total solids (dry weight basis) Salmonella sp., less than 3 MPN/4g total solids (dry weight basis)

Other entities such as the U.S. Composting Council (USCC) factor in more performance-related parameters to their compost quality standards. USCC organizes its compost quality standards by end use (USCC, n.d.), such as for growing flowers and vegetables (see *Table 7*).

Table 7: Compost parameters for flower and vegetable garden use (USCC, n.d.).

Parameter	Unit	Preferred Range	Acceptable Range	Notes
Stability[30]	mg CO_2-C per g OM per day	<2	<4	The lower the number, the more completely composted the product.
Maturity[31]	Percent seed emergence & vigor	90 - 100	80 - 100	The higher the percentage, the more versatile the product.
Moisture content	Percent wet weight basis	40 - 50	35 - 65	Products with higher moisture contents may be used. They may simply be more difficult to apply.
Organic matter content	Percent dry weight basis	35 - 60	25 - 65	Creating a soil containing 5% - 10% organic matter is desirable in typical, well drained soils.
Particle size	Screen size to pass through	3/8"	1/2"	Planting compost should be finely (3/8" – 1/2") screened, whereas coarsely screened compost (1: - 2") should be used in mulching.
pH	pH units	6.0 – 7.5	5.5 – 8.5	Modify soil pH with lime, etc., if necessary, based on soil testing results.
Soluble salts (EC)	dS/m (mmhos/cm) dry weight basis	Maximum of 5	Maximum of 15	Most soluble salts are also plant nutrients. Compost containing a higher soluble salt content should be applied at lower application rates, and 'watered in' well.
Physical contaminants	Percent dry weight basis	<0.5	<1	Small stones may be deemed more acceptable than man-made inerts (*e.g.,* plastic).

**All federal and state standards related to biological and chemical contamination must also be met.*

Regulation-wise, state and local governments in the U.S. set composting policies and quality standards for their jurisdictions (US EPA, 2025). The only federal standards for compost are those of:

1) the National Organic Program for compost used in certified organic operations, which has requirements for feedstocks and process parameters, but not attributes of finished compost [7 CFR 205.203(c)(2)]; and
2) the EPA's standards for sewage sludge, which include limits on pollutants (40 CFR 503.13).

Notwithstanding regulations and industry standards, professional compost end-users may evaluate additional or more specific compost quality criteria. Horticultural professionals in one report considered the USCC guidelines to be too general for a given use in a defined location, and recommended considering them as minimum quality standards (Sullivan & Miller, 2001). They noted that a given compost quality assurance program may only include a few of the parameters important to high-value horticultural use, thus making it necessary for the horticulturalist to evaluate additional specific criteria (Sullivan & Miller, 2001).

Many factors affect compost quality, and compost quality is site- and use-dependent. Agricultural researchers often look at how plants respond to a compost to assess its quality. A high-quality compost is not toxic to plants but supports seedling germination and plant growth (Bernal et al., 2017; Wyman & Salmon, 2024). Peña et al. (2020) proposed measuring compost quality as the sum of desirable attributes expressed in a chosen indicator species

[29] The regulation states that, "Although there is no maximum acceptable metal concentration for chromium in compost, operators subject to subdivision (a) shall arrange for concentrations of chromium in compost they produce to be determined in connection with the analysis of other metals. Operators shall maintain records of all chromium concentrations together with their records of other metal concentrations."
[30] Compost stability describes a compost's advanced stage of organic matter decomposition, which minimizes its potential to tie up nitrogen when applied to the soil. Stable volume and temperature also characterize compost at this stage (Sullivan & Miller, 2001).
[31] Compost maturity indicates the degree to which the composting process is complete. Indicators can include slowed or stopped biological activity of microorganisms metabolizing organic matter due to the exhaustion of available carbon sources (Bernal et al., 2017) and lack of phytotoxicity. Mature compost is dark in color and has a less pungent odor (Anunciado et al., 2021).

grown in that compost. We subsequently discuss research that uses germination and plant growth to evaluate the quality of composts. One drawback of assessing compost quality based solely on short-term plant response is that contaminants can go undetected if they do not impact these parameters.

What factors influence compost quality?

Compost feedstocks are widely variable in terms of their source, identity, and composition, but their characteristics are what primarily determine the quality of a finished compost (Sikora & Sullivan, 2000; Stehouwer et al., 2022). The combined initial carbon-to-nitrogen ratio (C:N) of feedstocks is critical to a successful composting process. An initial C:N ratio of 25:1 – 30:1 for compost feedstocks is typical, but Bernal et al. (2017) advised compost operations use a feedstock mixture with higher initial C:N ratio of 40:1 – 50:1, to minimize nitrogen volatilization during the composting process. Composting process parameters (aeration, duration, moisture) are other crucial factors. Feedstocks with an appropriate C:N ratio combined with conditions that maintain aeration and a moisture content of around 60% initiate the microbially mediated composting process, wherein the temperature rises and organic carbon is metabolized, or humified, as described in *Focus Question #3*. These factors are significant determinants in final compost quality (Peña et al., 2020). Other feedstock attributes that influence final compost quality include nutrient content, pH, particle size and porosity, the biological composition of bacteria, fungi, viruses, pathogens, and the presence of non-degradable materials, which have to be screened out or otherwise excluded from the finished compost so as not to compromise quality (Bernal et al., 2017).

What are the soil benefits of applying compost?

The benefits of incorporating compost into agricultural soils include (Bolan et al., 2021; Brändli et al., 2005; Clemente et al., 2015; Huerta-Lwanga et al., 2021; Sullivan & Miller, 2001):

- increasing soil organic matter content
- enhancing soil microbial activity
- improving water infiltration, water holding capacity, and hydraulic conductivity
- increasing cation exchange capacity
- stabilizing soil structure by enhancing soil aggregate stability
- reducing erosion
- providing a source of slow-release nutrients for plants

What research is available on the quality and soil benefits of composts containing compostable materials?

Most of the literature on compostable food packaging focuses on the materials' physical breakdown under controlled composting conditions (Choi et al., 2019) rather than the quality of the resulting compost. Wyman and Salmon's (2024) survey of lab studies on compostable materials and products uncovered few reports that evaluated compost quality. We describe below several compost field trial studies that did evaluate the impacts of compostable products on certain compost quality parameters. We also review studies that examine the effects of microplastics in soil, specifically microplastics from materials that are commonly used in compostable products. The available research is disparate in terms of materials, methods, and parameters measured. As a result, the conclusions across studies are not uniform or consistent but are specific to the given study from which they derive. General trends are still elusive, and most investigators cite a need for more research (Boots et al., 2019; Chah et al., 2022; de Souza Machado et al., 2019; Falzarano et al., 2024; Rillig et al., 2021; F. Wang et al., 2022).

Over the last several decades, product manufacturers, consumers, governments, and other entities have increasingly looked for ways to reduce plastic waste (Goldstein & Coker, 2021), and have identified products specially designed to be composted as a promising solution. Some researchers have found that using compostables as compost feedstocks does not negatively impact compost quality. Greene (2007) looked at yard-waste compost samples that included cornstarch-based garbage bags, sugarcane-based plates, polylactic acid (PLA) cups, or PLA containers, versus controls containing cellulose and kraft paper. The samples had been composted over a period of 20 weeks. The PLA cup, knife, container, and kraft paper control degraded 100% in the compost after 20 weeks. The corn starch trash bag and sugarcane plate were 84% and 78% degraded, respectively. The author found no significant difference between tomato seed germination in composts with the various compostable products, suggesting the materials did not have phytotoxic effects. The study did not report concentrations for the compostable materials in the composts (J. Greene, 2007).

Individual studies of compost made with compostables

Klauss and Bidlingmaier (2004) measured the quality of compost made from municipally-collected organic waste that included biodegradable biopolymers. The study was part of a pilot project where the city of Kassel, Germany introduced compostable bioplastics into the marketplace, informed consumers about the products' proper disposal, and then tracked the products' collection and handling at municipal composting facilities. The concentration of bioplastic in the finished compost was small: 1%, possibly due to removal by composting personnel. They assessed the following parameters in subsequent field trials with the compost:

- organic matter content
- pH
- dry matter
- rotting degree
- mass of impurities
- visual contaminants
- zinc concentration (as an indicator of heavy metal contamination)
- crop growth and quality

The authors found no difference between the quality measures of soils receiving composts made from organic wastes with 1% bioplastics versus composted organic wastes without bioplastics, including no difference in yield of Chinese cabbage (Klauss & Bidlingmaier, 2004).

Huerta-Lwanga et al. (2021) evaluated the effects PLA polymer residues in compost on earthworm mortality, plant growth, and soil physiochemical conditions. They did not find significant effects of PLA residues at concentrations of up to five percent on any of the parameters measured. The authors did observe that *Lumbricus terrestris* earthworms ingested and transported microplastics into their burrows when the microplastics were present at one percent PLA concentration (Huerta-Lwanga et al., 2021). They did not explore further the fate or impacts of the ingested and transported microplastics in this study, but acknowledged the need for longer-term research with more replicates (Huerta-Lwanga et al., 2021).

Unmar and Mohee (2008) compared the quality of composts made from greenwaste and degradable plastic bags (polyethylene or polypropylene with 2.5-3% PDQ-H additive), greenwaste and biodegradable plastic bags (starch-based Mater-Bi), and compost from just greenwaste. The PDQ-H additive facilitates oxidation and photodegradation of the plastic, while the starch-based plastic dissolves in air and water in 45 days. The researchers assessed compost quality in terms of nutrient content, as well as germination of mustard seeds. They found that the plastic residues in the composts tested did not impact mustard seed germination or show an inhibitory effect on plant growth. The nutrient content was highest in the compost made from greenwaste + biodegradable plastic bags (3.01% nitrogen, 1.03% phosphorus, and 1.62% potassium), which also showed the longest radicle lengths of seeds in the phytotoxicity trial. The pH was neutral for all samples (7.4-7.7). These results led the authors to conclude that inclusion of the biodegradable plastic feedstock did not impact the quality of the compost (Unmar & Mohee, 2008). The compost made using degradable plastic with the PDQ-H additive still had 2% visible remnants of plastic at the end of the composting process, which lasted approximately 56 days (Unmar & Mohee, 2008).

The research noted above did not find negative impacts of compostable products on compost quality; however, these were all short-term studies, at 20 weeks or less. They did not assess complete biodegradation or the long-term impacts of microplastics on soil quality and plant growth. Their findings are also in contrast to other studies that have shown adverse effects from residues of compostable products on soil quality and plant growth (Boots et al., 2019; Chah et al., 2022).

PFAS

One investigation of PFOA, a PFAS contaminant found in some compostable food contact materials, revealed that PFOA can inhibit the humification process in composting (He et al., 2024). In their study, the researchers added 15.5 µm/kg dry weight PFOA to feedstocks and then closely monitored the composting process and microbial and enzymatic activity over the next 30 days.[32] The authors (2024) found that PFOA altered the way microorganisms metabolized organic matter. Microorganisms shifted from anabolic (biomass production) to catabolic (energy-yielding, CO_2-producing) pathways, which suggested oxidative stress. The result was lower rates of fulvic and humic substance formation in the initial stages of composting and decreased organic matter content. The authors therefore concluded that PFOA inhibits humification during the composting process (He et al., 2024).

Microplastics

The decomposition of some compostable products results in microplastics. Microplastics are another major soil contaminant of concern (Ainali et al., 2022), and the focus of a growing body of research. Microplastics are particles smaller than 5 mm and may be residues of both fossil fuel and bio-based plastics (Huerta-Lwanga et al., 2021). According to Wang et al. (2022), mulch films are the major source of microplastics in agricultural soils. However, microplastics can also result when compostable products degrade more slowly than the rest of the feedstocks in a

[32] This concentration is slightly greater than the 10.3 µm/kg concentration PFOA that Choi et al. (2019) found in commercial compost that included food contact materials as feedstocks.

compost (J. Greene, 2007; Unmar & Mohee, 2008). The proportion of non-degradable materials increases during the composting process (Bernal et al., 2017). In this way, microplastics accumulate in compost, and compost application then transfers them to the soil. Bioplastics or plastics designed to be compostable degrade at a lower rate in the soil than under composting conditions (Ainali et al., 2022). Depending on the material and the environment, some but not all bioplastics break down faster than conventional plastics in the soil. When they do, they go through more physical and chemical changes in the soil in shorter periods of time, resulting in greater impacts on the soil ecosystem than conventional counterparts (Gong et al., 2024).

Microplastics in compost, including those from biodegradable plastics used in compostable products, can affect soil parameters and plant performance. The addition of PLA microplastics to soil increases the soil C:N ratio, reduces pH, and increases electrical conductivity (R. Liu et al., 2023). A higher soil C:N ratio leads to decreased nitrogen availability for plants, as microbes immobilize nitrogen to metabolize carbon (R. Liu et al., 2023; Rillig et al., 2021; Seeley et al., 2020).

Gong et al. (2024) evaluated the impact of microplastics from PLA and polybutylene adipate terephthalate (PBAT) in different soils and conditions. They found that biodegradable microplastics changed microbial communities in different ways depending on soil moisture conditions. For example, drier soil with PBAT microplastics showed enhanced microbial ammonia production compared to flooded or alternating dry and wet soil conditions (Gong et al., 2024).

Boots et al. (2019) conducted a laboratory study that incorporated PLA microplastics ranging in size from 0.6 to 363 µm into a soil at 0.1% concentration. They found that bioplastic residues reduced the formation and stability of soil aggregates, possibly by interrupting cohesion between soil particles (Boots et al., 2019). They also found a significant decrease (7% reduction) in seed germination of perennial ryegrass (*Lolium perenne*) between microplastic-contaminated soil and controls. Shoots were 19% shorter in the PLA soil vs. control. There was no significant difference in total chlorophyll content between the treatment and control, but plants grown in the PLA soil did show a greater proportion (22% increase) of chlorophyll-a to chlorophyll-b as compared to the control (Boots et al., 2019).

Liu et al. (2023) found even more pronounced results when growing corn in soils containing PLA microplastics at various concentrations. A concentration of 0.1% PLA did not significantly impact the root and shoot biomass of corn, but 1%, 5%, and 10% PLA residues did, by 32%, 63% and 69%, respectively, for shoots, and 30%, 47%, and 53%, respectively, for roots. In their study, chlorophyll a and b levels decreased at 1% PLA concentration and greater. These higher concentrations of PLA residues also depressed the C and N content of plant leaves and roots in the study.

Literature review studies

Chah et al. (2022) reviewed 632 reports on bioplastic research since 1973. Only 9.7% of studies evaluated the impacts of bioplastics on the environment, and most were short term rather than long term. Of all the focus areas, those least studied were the effects of bioplastic residues on soil properties like aggregate stability, bulk density, porosity, electrical conductivity, cation exchange capacity, and hydraulic conductivity (Chah et al., 2022). The scant reporting on the impacts of bioplastics on soil properties shows variable effects depending on the type of bioplastic, its shape, size, additives, chemical composition, biodegradation pathways, and concentration in the soil (Chah et al., 2022; Rillig et al., 2021). De Souza et al. found that microplastic fragments that had similar shapes as soil particles did not affect plant growth or modify soil properties to the same extent as microplastics with long, thin, fiber shapes. Chah et al. (2022) suggested that biodegradable plastics have similar impacts on soil properties as conventional plastics in the short term but have drastically different behavior as they go through different stages of biodegradation compared to non-biodegradable plastics. In addition to their variable effects on soil properties, microplastics also sorb toxic compounds in the soil onto their high-surface-area polymeric backbone through various mechanisms, and transport them in the environment (Ainali et al., 2022).

Zhang et al. (2022) performed a meta-analysis of studies evaluating the ecological impacts of microplastics, including bioplastics, on plant growth. They found inconsistent effects of microplastics on plant growth between studies. Some studies reported that microplastics impact plant growth and cause oxidative stress to plants as detected in the antioxidant enzyme indicators, and their corresponding substrates and products (J. Zhang, Ren, et al., 2022). Other studies reported no impacts on plant growth, while others showed positive impacts. Different bioplastics can have different impacts on soil physical properties, which indirectly affects plant growth in different ways. The authors emphasized the need for long-term studies to further assess the impacts of bioplastics on soils and plants (J. Zhang, Ren, et al., 2022).

Afshar et al. (2024) also conducted a systematic literature review on the environmental fate of biodegradable plastics, including in compost management systems. They determined that there was a lack of research on compost quality for several types of biodegradable plastics (PBS, PBAT and PHA). They reviewed articles on the quality of compost containing PLA and starch-based feedstocks, and the effects on subsequent seed germination, plant growth, yield, and nutrient content. The authors found that, according to the available research, compost quality may not be affected by low concentrations of biodegradable plastics, but reiterated the need for more research on the effects of bioplastics on compost quality and the environment (Afshar et al., 2024). The scientific community is in agreement that the ecological impacts of bioplastics, and the mechanisms by which they affect soils and plants, are poorly understood and require further study (Boots et al., 2019; Falzarano et al., 2024; R. Liu et al., 2023; Rillig et al., 2021; Y. Wang et al., 2024).

Authors

The following individuals participated in research, data collection, writing, editing, and/or final approval of this report:

- Peter O. Bungum, Research and Education Manager, OMRI
- Tina Jensen Augustine, Technical Operations Manager, OMRI
- Jarod T Rhoades, Standards Manager, OMRI
- Jacky Castañeda, Bilingual Technical Research Analyst, OMRI
- Marie Gipson, Technical Research Analyst, OMRI
- Colleen E. Al-Samarrie, Technical Research Analyst, OMRI
- Aura del Angel A Larson, Bilingual Technical Research Analyst, OMRI
- Doug Currier, Technical Director, OMRI
- Ashley Shaw, Technical Research and Administrative Specialist, OMRI

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Appendix

Table 8: Properties of common biodegradable polymer materials.

Primary Materials	Fillers	Additives	Item Types	References
Starch-based polymers (biobased, biodegradable)				
Chitosan	Nanocellulose; rice husk	Silver nanoparticles and some metal oxides (*e.g.,* zinc oxide nanoparticles and titanium dioxide nanoparticles); halloysite, bentonite, kaolinite	Films and food-contact packaging coating	(Jin et al., 2024; Nath et al., 2022; Siddiqui et al., 2024)
Cassava	Coconut fiber; nanocrystalline cellulose from kenaf fiber	Kaolin; plasticizers can include glycerol and sorbitol		(Siddiqui et al., 2024; Surendren et al., 2022)
Corn starch	Sugarcane bagasse, coffee husk, rice husk, date palm fiber; corncob cellulose	Glycerol, montmorillonite, polycaprolactone, ZnO nanoparticles, anthocyanin extract, lecithin, oleic acid, sunflower oil, cassia seed oil; sorbitol, xylitol, urea, ethanolamine, thymol, 1-ethyl-3methylimidazolium acetate	Food trays; multi-layer film; gas and aroma barrier film	(Y. Cui et al., 2024; Ghasemlou et al., 2024; Siddiqui et al., 2024; Surendren et al., 2022)
Potato starch		SiO2 nanoparticles, zine nanoparticles, anthocyanin extract; glycerol, sorbitol, 1-ethyl-3-methylimidazolium acetate, kaolin clay	Flexible bags, pouches, jugs, handle bags, trash bags, agricultural & industrial films	(Y. Cui et al., 2024; Surendren et al., 2022)
Rice starch	Cotton fiber	Blueberry agro-industrial waste, oregano essential oil; plasticizers can include glycerol and sorbitol		(Y. Cui et al., 2024; Surendren et al., 2022)
TPS (Thermoplastic starch)	Chitosan	Plasticizers can include glycerol, glycol, and sorbitol; SiO2 nanoparticles	Carrier bags, fruit and vegetable bags, bio-waste bag, mulch film, non-woven fibers	(Ghasemlou et al., 2024; Siddiqui et al., 2024; Surendren et al., 2022)
Cellulose-based polymers (biobased, biodegradable)				
MCC (Microcrystalline cellulose); the most effective method for extracting cellulose from bio sources typically involves a combination of alkaline and acid hydrolysis, followed by bleaching by oxidation.	Flax, wheat straw, soybeans hull, bagasse, pineapple leaf, oil cakes, hemp straw, rice husk			(Techawinyutham et al., 2025)
CMC (Carboxymethyl cellulose)	Walnut shell powder	Glycerol as a plasticizer; citric acid and vanillin as cross-linking agents	Flexible film	(Plaeyao et al., 2025; Qian et al., 2025)
Aliphatic polyesters (fermentation biobased, biodegradable)				
PLA (Polylacticacid); the production of this material involves condensation polymerization of lactic acids and commercial synthesis of lactic acids is commonly sourced from the bacterial fermentation of sugars; potential feedstocks are sugarcane, corn, potato, cassava roots, sugar beet	Corn fibers, sugarcane bagasse, snail shell, esparto grass alfa fibers, coconut shell powder; starch, wood flour, chitosan, sisal fibers, okra fibers, olive husk flour, paddy straw flour	Halloysite; plasticizers can include acetyl tributyl citrate (ATBC), tributyl citrate (TBC), and polyethylene glycol (PEG), vegetable oils, citric acid, oleic acid, sebacic acid, adipic acid, succinic acid, cardanol, and isosorbide	Flexible films (*e.g.,* tea bags and frozen vegetable bags) or rigid bottles (*e.g.,* yogurt); mulch films and hot drink/food packaging	(Afshar et al., 2024; Ali et al., 2023; Ghasemlou et al., 2024; Nath et al., 2022; Siddiqui et al., 2024; S. Sun et al., 2024)

Primary Materials	Fillers	Additives	Item Types	References
Aliphatic (co)polyesters (partial biobased, biodegradable)				
PBS (Polybutylene succinate); succinic acid derived from biomass and petroleum-based 1,4-butanediol; potential feedstocks include sugarcane, cassava, and corn; manufacturers can make bio-PBS partially bio-based with succinic acid derived from renewable feedstocks (corn, sugarcane, etc.) and the butanediol (BDO) monomer is petroleum based, bio-BDO from renewable feedstocks is theoretically possible and may be available in the future		Plasticizers can include materials derived from epoxidized soybean oil, castor oil, cardanol, citrate, and isosorbide	Hot beverage cups, food boxes, and cutlery	(Afshar et al., 2024; Alhanish & Abu Ghalia, 2021; Ghasemlou et al., 2024)
PBSA (Polybutylene succinate-co-adipate); the succinic acid is biobased, but the 1,4-butanediol and adipic acid are petroleum-based			Waste bags, flowerpots, bottles, trays	(Afshar et al., 2024)
Aliphatic-aromatic (co)polyesters (petroleum-based, biodegradable)				
PBAT (Polybutylene adipate terephthalate); fully petroleum-based copolymerization of adipic acid, 1,4-butanediol, and aromatic terephthalic acid monomers	PLA and starch	Plasticizers can include materials derived from epoxidized soybean oil, castor oil, cardanol, citrate, and isosorbide; SiO_2 nanoparticles	Cling/wrap films for fresh foods, shopping bags, and mulch films	(Alhanish & Abu Ghalia, 2021; Ghasemlou et al., 2024; Siddiqui et al., 2024)
PBST (Polybutylene succinate-co-terephthalate); manufacturers swap the adipic acid fraction of PBAT for biobased succinic acid (*i.e.,* ~35% total biobased material)		Plasticizers can include materials derived from epoxidized soybean oil, castor oil, cardanol, citrate, and isosorbide		(Alhanish & Abu Ghalia, 2021; Ghasemlou et al., 2024)
Other (biobased, biodegradable)				
Keratin (from chicken feathers)	MCC			(Siddiqui et al., 2024)
Plant protein isolates (*e.g.,* soy, gluten, zein protein)	Methylcellulose	Glycerol		(Bagnani et al., 2024)
Seaweed extracts (*e.g.,* carrageenan and alginate)	MCC; cellulose/ montmorillonite (MMT), cassava starch			(Siddiqui et al., 2024)