COMPOSTABLE PLASTICS IN THE WASTE STREAM: MANAGEMENT SCENARIOS AND LIFE CYCLE IMPACTS

by

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(Under the Direction of Jenna Jambeck)

ABSTRACT

Biodegradable plastics are increasingly popular as functional substitutes for some packaging applications of inert plastics. Biodegradation in the event of mismanagement may reduce accumulation of packaging in natural environments, but biodegradable plastics will also impact managed waste streams. In this study, the fate of biodegradable plastics at end-of-life is examined through the infrastructure necessary to recycle organic wastes in the United States with a focus on the Southeast. A Life Cycle Assessment (LCA) framework is proposed to examine the impacts of biodegradable plastics in both managed and mismanaged pathways at end-of-life, with a focus on landfilling and aerobic composting. A case study is undertaken for the community of greater Athens, Georgia and compares waste management of PLA clamshells, MaterBi bags, PHA straws and LDPE film. Materials that are highly biodegradable result in climate change impacts in landfilled scenarios. Minimizing contamination of compost piles reduces overall environmental impacts associated with composting.

INDEX WORDS: waste management, Life Cycle Assessment, compost, landfill, plastics, packaging, biodegradable, circular economy

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by

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CHAPTER 1: INTRODUCTION

1.1 Plastic Packaging Waste in the U.S.

Growth in plastic production has been driven by a number of applications, of which packaging is the largest. About 42% of all non-fiber plastics ever made have been used for packaging (Geyer, Jambeck, & Law, 2017). Plastics are particularly well suited to packaging - light, water-resistant, flexible and customizable (Andrady & Neal, 2009). The utility and low cost of plastic packaging coupled with an increasing consumer demand has translated into an ever-larger stream of plastic waste. Generation of plastic packaging waste in the United States was first estimated by the Environmental Protection Agency (U.S. EPA) in 1960. Estimated generation for 2018 totaled over 14.5 million tons **(Fig 1)** (U.S. EPA, 2020).

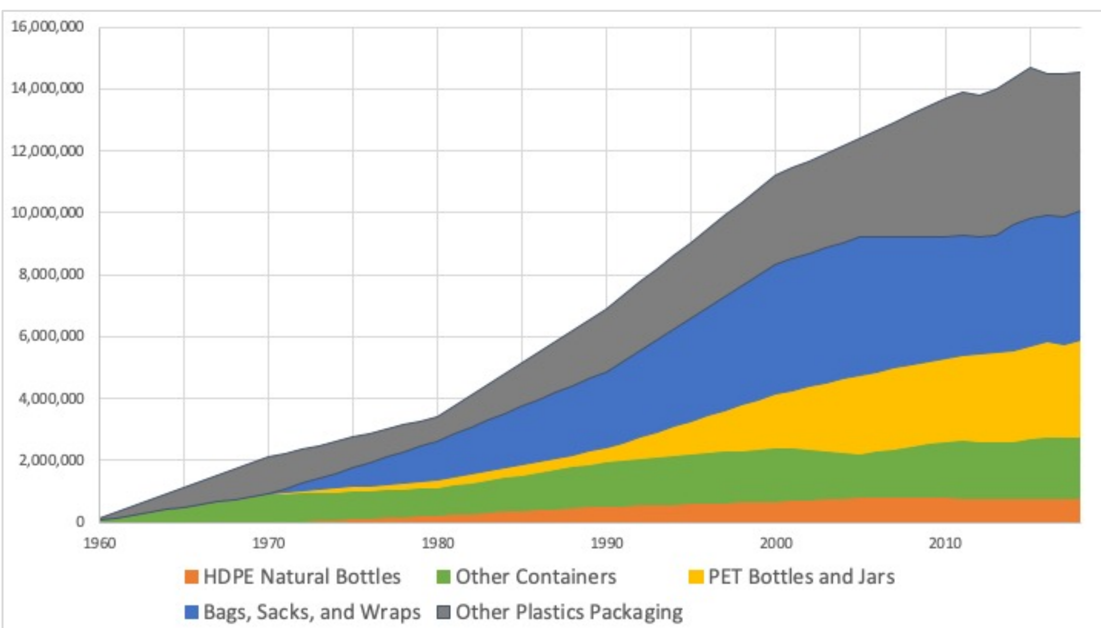

Figure 1: Annual Plastic Packaging MSW Generation in tons, 1960 – 2018 (U.S. EPA, 2020). Values are stacked and shown as a portion of total packaging waste generation, 14.5 million tons in 2018

As plastic packaging waste generation has grown, it has introduced a number of challenges to the U.S. waste management sector. Plastic waste in managed environments can cause problems over time related to land requirements, "leakage" from systems, challenges to recycling stemming from the variety of plastics in the market, and cost to build and maintain waste management infrastructure. The majority of U.S. plastic packaging waste is landfilled **(Fig 2).** A small amount is incinerated, mainly in the Northeast, and a small amount is recycled – 13% in 2017 (U.S. EPA, 2020). However, these figures do not paint a full picture of the ultimate fate of plastics that are counted by the EPA as "recycled." Plastics that are recovered for recycling are increasingly subject to market conditions that may limit or altogether prevent their valorization potential – an issue that has gained significance as trade partners that we have historically relied on to import and process our plastic waste have enacted restrictions on their imports (Brooks, Wang, & Jambeck, 2018).

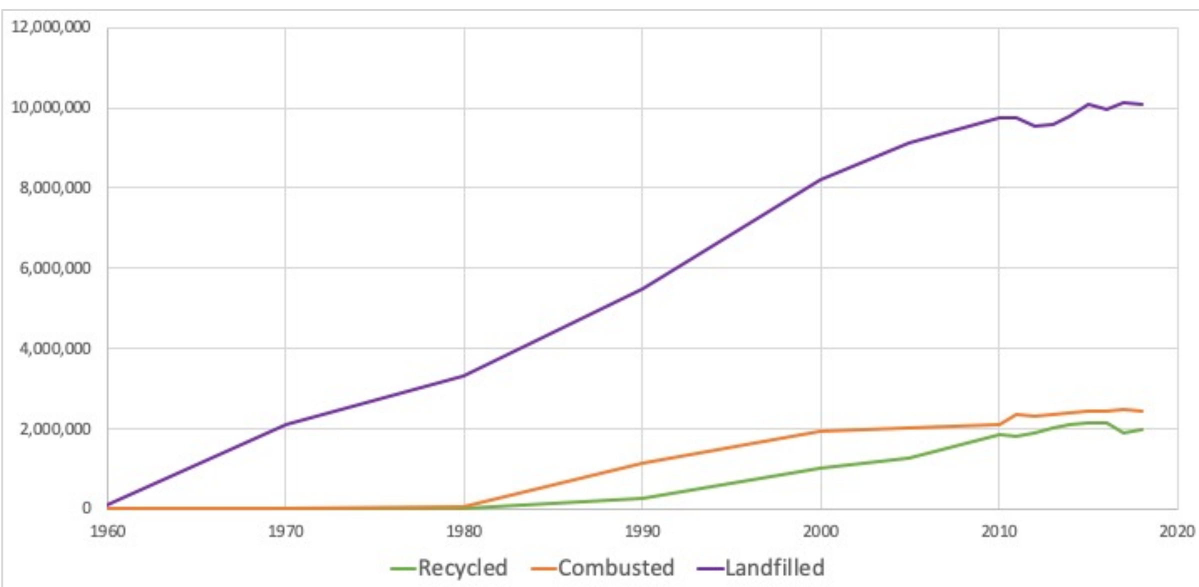

Figure 2: Plastic Packaging Management, 1960 – 2018
(U.S. EPA, 2020)

Plastic packaging waste is also often mismanaged through leakage from littering and illegal dumping. Domestic *rate* of plastic waste mismanagement (measured per unit waste generated) in the U.S. is relatively small when considered on a global scale, but plastic waste generation per capita in the U.S. is among the highest in the world. Estimates for 2016 put the domestic mismanagement of plastic waste at 1 million metric tons or more (Law et al., 2020). When export to countries lacking adequate management is included, estimated 2016 total U.S. contributions to plastic waste in the environment range from 1.13-2.24 million metric tons (Law et al., 2020). A growing body of evidence points to lasting effects on both ecosystem and human health stemming from plastic accumulation in the environment, even after it has fragmented into microscopic particles (Worm, 2017). A number of ambitious mitigation strategies must be undertaken in tandem in order to make a meaningful dent in the amount of mismanaged plastic waste in the environment. Effective capture by waste management systems should and must be paired with material substitution, design optimization, technological innovation and recycled content standards (Borrelle et al., 2020). Elimination and substitution of inert plastic packaging materials with materials that are less prone to accumulation and more readily degradable is one strategy that is pointed to as a necessary component of this suite of interventions (Lau et al., 2020).

1.2 Plastic Waste Management and 'Circularity'

Increased visibility around plastic waste in the environment has led to widespread concern; a broad-based consensus has emerged in recent years that plastic packaging waste generation and management is in need of an overhaul. Governments and private sector organizations alike have enacted plans with this objective, spurring increased investment in plastic waste management infrastructure and material substitution. Many of these plans and discussions around interventions in waste and materials management have been framed to some degree in the concept of the Circular Economy (CE), which envisions a world where materials are circulated in infinite loops and kept in use for as long as possible (Korhonen, Honkasalo, & Seppälä, 2018) (**Fig 3**). In particular, many large multinational companies including Walmart and Nestle have focused on design for circular waste management and have signed onto an initiative calling for 100% recyclable or compostable packaging by 2025 (Ellen Macarthur Foundation, 2018). The US Plastics Pact announced in 2020 calls for this same goal as well as an added target of the effective recycling or composting of 50% of plastic packaging by 2025 (Ellen Macarthur Foundation, 2020). However, both composting and recycling infrastructure are currently unable to capture all plastic packaging waste streams and a massive increase in capacity and throughput will be needed to meet these targets even if some packaging types are eliminated.

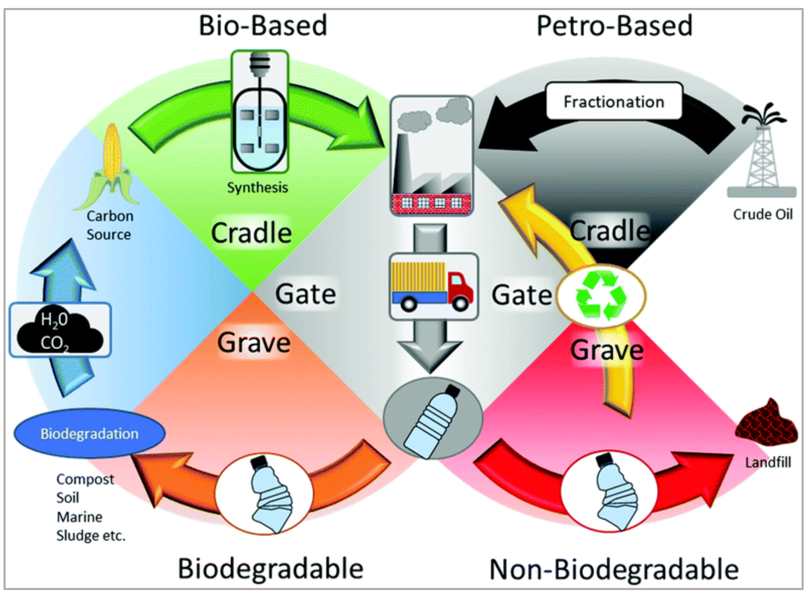

Figure 3: "Circular" plastic waste management
(Meereboer, Misra, & Mohanty, 2020). Cradle to Cradle vs Cradle to Grave

Material Flow Analysis (MFA) for plastics production, use and end-of-life (EOL) in the U.S. has demonstrated that even plastics such as PET that have the highest rates of recycling face significant challenges in realizing "closed-loop" outcomes for recycling, and a majority of PET is still managed in landfill. The recycling rate for PET bottles in the US in 2017 was 29%, which indicates the amount of PET bottles collected and recovered after use; however, the "utilization rate" (the amount actually estimated to go back into new products) for material from

PET bottles was only 20.9% (Heller, Mazor, & Keoleian, 2020). This discrepancy is due to a number of factors. A significant factor is contamination with non-PET material in recycled bales. Contamination levels vary by geography and waste management policy. States with bottle bill deposits generally have cleaner bales that are more suitable for “closed-loop” recycling into food-grade PET packaging material; on the other hand, communities with single stream recycling systems often send their more highly contaminated bales to be “down-cycled” into more durable plastic goods such as textiles; and excessive amounts of contamination can make any recycling cost-prohibitive (Waste Management, 2020). Recycling and utilization rates for other plastic packaging types are even lower and improving these metrics will require large-scale investment and optimization. Flexible and light film plastics face unique challenges. Much of the waste management infrastructure in the form of Material Recovery Facilities (MRFs) are not designed to capture of these materials. In addition, plastic packaging design incorporates many elements. Complexity for desired characteristics in terms of both product protection and marketable appearance can prevent processing altogether. Food packaging has the added challenged of likely contamination by food residue.

Because of the challenges with effective recycling of some types of plastic packaging, stakeholders looking for alternatives that enable ‘circular’ waste management are increasingly interested in compostable packaging materials. Private sector commitments like that of the Plastics Pact are accompanied by an increased number of governments who have enacted policies focused on plastic waste pollution and landfill diversion. Several such policies explicitly favor compostable products as a substitute for other types of single-use plastic packaging. Local to Georgia, Atlanta City Council announced a ban on city purchase of single use plastic bags, styrofoam and straws but carved out an exception for compostable products ("Use of non-compostable single-use serviceware prohibited," 2019). The city of South Fulton enacted a similar ban in early 2021 that extends to privately owned retailers (City of South Fulton

Government, 2021). Legislation introduced on the national stage last year that calls for a ban on many classes of single use plastic names compostable products as a preferable alternative for food contact and landfill diversion ("Break Free From Plastic Pollution Act," 2020).

However, waste management infrastructure for composting of organic wastes is limited. Producers of plastic packaging designed to be compostable face the reality that many of these materials may continue to be managed through landfilling or incineration. Stakeholders in both packaging design and waste management may not always understand how compostable plastics biodegrade, and consideration also needs to be given to the fate of compostable packaging materials that end up mismanaged in the natural environment. Investment in composting infrastructure that can effectively process these materials alongside other types of organic wastes is needed to ensure their successful intended end-of-life (EOL).

Understanding the infrastructure necessary to enable management of compostable packaging waste is especially relevant given the rising popularity of Extended Producer Responsibility (EPR). EPR is a policy tool that requires producers and upstream stakeholders in manufacturing and distribution of packaged goods to ensure responsible disposal of packaging, usually targeting landfill diversion and minimization of leakage into the environment. EPR often requires packaging producers to reimburse waste managers for costs incurred in management of packaging materials, or finance their own collection schemes. Increased understanding of the costs of waste management for compostable plastics from the perspective of waste managers and other stakeholders in organics recycling can add to the discussion around potential formation and implementation of EPR models for compostable plastic packaging in the future.

1.3 Objectives

The overall objective of this study is to present a framework using Life Cycle Analysis (LCA) and Life Cycle Costing (LCC) that allows for accounting of the impacts of compostable bioplastic packaging introduced into waste management systems, with a focus on the southeastern United States. This approach requires characterization of the waste management system in place before detailing potential pathways for compostable packaging waste. Greater Athens, GA is used as a case study for application of this framework.

A secondary focus of this study is characterization of the availability of composting infrastructure that currently manages post-consumer food waste and compostable packaging waste in the southeastern United States, and discussion of the challenges and opportunities involved in potential expansion of this infrastructure.

1.4 Outline of Remaining Chapters

- Chapter 2 introduces definitions and certification schemes for biodegradable and compostable packaging materials, and gives examples of their applications. Life Cycle Analysis (LCA) is also introduced in this chapter.
- Chapter 3 examines the current composting landscape in the United States and the perspective of composters on acceptance of compostable packaging gathered from surveys and interviews.
- Chapter 4 presents a literature review on End-of-Life in LCA, as well as how LCA is used for modeling and analysis of waste management systems through various tools.
- Chapter 5 focuses on the Southeastern United States and discusses the current waste management pathways for compostable packaging in this setting. Athens, GA is described in detail to illustrate the infrastructure components involved in management of compostable bioplastic packaging waste through a municipal operation.
- Chapter 6 incorporates LCA and LCC to assess and compare the impacts of waste management for compostable bioplastic packaging in the context of greater Athens, GA.
- Chapter 7 presents the results of this case study along with discussion of key findings and considerations for future work.

CHAPTER 2: BACKGROUND

2.1 Biodegradable and Compostable Plastics

Plastics that are designed to biodegrade in aerobic and/or anaerobic environments are a subset of bioplastics. The term bioplastics was coined by European Bioplastics and is used to refer to plastics that are biodegradable, biobased or both (EuropeanBioplastics, 2019). However, not all bioplastics are biodegradable (**Fig 4**). Drop-in bioplastics such as bio-PET are functionally the same as their fossil-based PET counterparts and will not exhibit enhanced degradation behavior. Biodegradable bioplastics can also be partially or fully fossil-based.

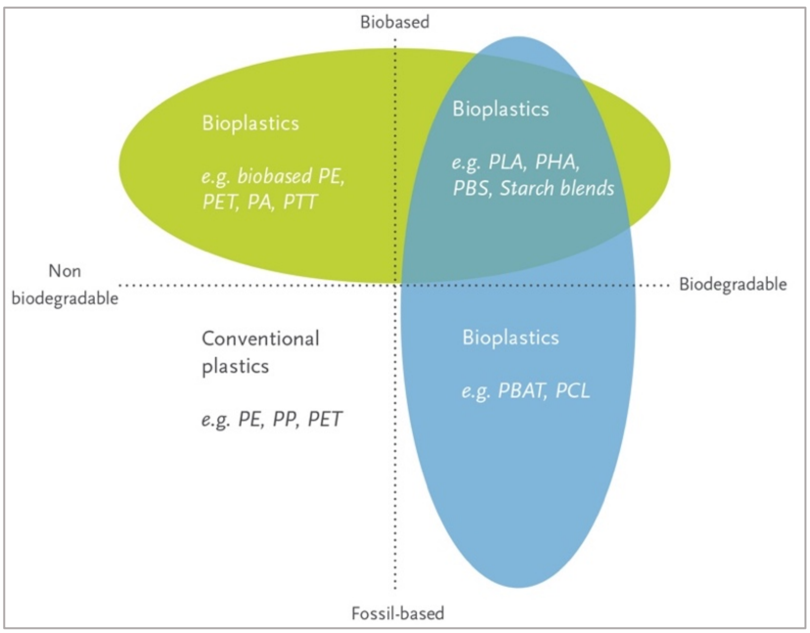

Figure 4: Bioplastics by material origin and biodegradability
(EuropeanBioplastics, 2019)

Biodegradation refers to the transformation of bioplastics or other organic materials in the environment by microbial organisms. Complete biodegradation results in carbon dioxide, methane (only if anaerobic), water and biomass (**Fig. 5**). The term biodegradable by itself, while useful, is often misleading when applied to bioplastic wastes as a material can be biodegradable but persist in natural or engineered environments for extended periods of time. Moisture, pH, oxygen level, temperature and microbial community all play a role in real-world biodegradation rates. Standards for measurement and certification of biodegradable materials in the US and EU often include provisions that ensure no toxic byproducts are formed during the sometimes extended biodegradation period, and specify upper limits on biodegradation times in certain environmental conditions (**Table 1**). However, due to widespread confusion around the meaning of the term “biodegradable” by itself, some state and local governments have banned used of the word on labels or advertisements in favor of compostable certifications ("Bag Requirements," ; "Environment - Compostable, Degradable, and Biodegradable Plastic Products - Labeling," 2017; Millar, 2020).

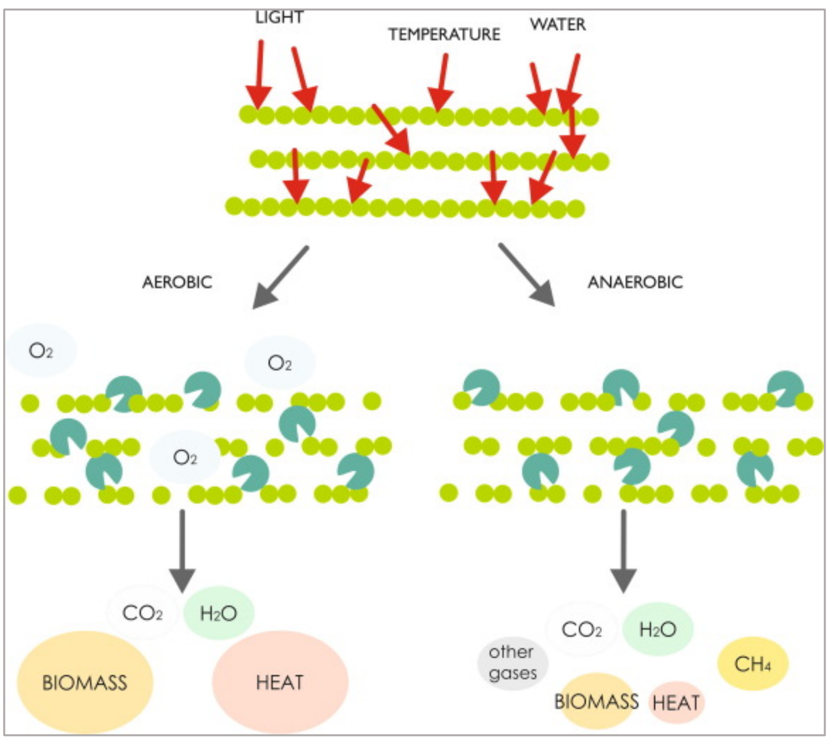

Figure 5: Biodegradation of biopolymers: aerobic and anaerobic degradation (Bátori, Åkesson, Zamani, Taherzadeh, & Sárvári Horváth, 2018). Dark green symbols represent the microorganisms involved in the processes

Bioplastics that readily biodegrade in conditions typical to industrial or home composting environments are referred to as compostable bioplastics. In the U.S. standards for industrially compostable product testing and labeling are governed by ASTM D6400, which specifies the percent of biodegradation that must occur in a certain timeframe under conditions that simulate industrial composting environments. The Biodegradable Products Institute (BPI) is the most widely used third-party certification for compostable food products and food packaging (**Table 1**). Industrial aerobic composting is suitable for management and controlled aerobic degradation of organic wastes such as yard trimmings, biosolids, and food scraps. Common technologies for industrial composting include windrows, aerated static piles and in vessel systems (N. Goldstein, 2017). Field testing certification in these different environments is formally provided and certified in the US by an association of compost facilities and their partners known as the Compost Manufacturer's Alliance (CMA), although field testing is also undertaken by composters who may operate outside of the CMA network (**Table 1**).

Table 1: Testing and Certification Standards for Biodegradable and Compostable Materials
(ASTM International, 2018a, 2018b, 2019; Bastioli, 2020; Hann, 2020)

Environment	Governing Body and Standard	Test duration and measurement type(s), criteria	Labeling / certification
Industrial Compost, aerobic	ASTM D6400 (US)	Minimum of 90 days up to 180 days at thermophilic temperatures in compost inoculum, must biodegrade 90% as measured by CO_2 and have less than 10% of original dry weight remaining. Germination rate and plant biomass tests	Biodegradable Products Institute (BPI) uses this test as the basis for their certification in addition to extra financial/compliance requirements
Industrial Compost, aerobic	EN 13432 (EU)	Up to 6 months at thermophilic temperatures in compost inoculum, must biodegrade 90% as measured by CO_2. Must disintegrate and have less than 10% of original dry weight	OK compost industrial, TUV Austria seedling, DIN Industrial Compostable

		remaining in 12 weeks. Germination rate and plant biomass tests	
Industrial Compost, aerobic	Compost Manufacturing Alliance (CMA) (US)	This test requires ASTM 6400 or EN 13432 compliance before it is undertaken, and uses field testing in a network of composting facilities	“Composter Approved” or other Cedar Grove/CMA label
Home Compost, aerobic	TUV OK compost HOME, DIN Home Compostable	Must biodegrade 90% as measured by CO_2 in 12 months at ambient temperature in compost inoculum, 90% disintegration in 6 months, non-toxic	OK compost home, DIN Home Compostable
Sea water, aerobic	ASTM D6691	Seawater inoculum at 30 C, usually up to 90 days but can be extended, % biodegradation reported, non-toxic	none
Sea water, aerobic	TUV OK biodegradable MARINE	Seawater inoculum at 30 C, must biodegrade 90% within 6 months and 90% degradation in 12 weeks, non-toxic	OK biodegradable MARINE
Soil, aerobic	ASTM D5988	Soil inoculum at 20-28 C, % biodegradation time and % reported, non-toxic	none
Soil, aerobic	TUV OK biodegradable SOIL, DIN biodegradable in soil	Soil inoculum at 25 C, 90% biodegradation within 2 years, non-toxic	OK biodegradable SOIL, DIN biodegradable in soil
Sewage sludge, aerobic	ASTM D5271	Water with activated sludge from water treatment at 23 C, biodegradation 60% within 6 months	none

High-solids anaerobic digestion	ASTM D5511	Inoculum from anaerobic digester of household waste at 52 C (thermophilic) or 37 C (mesophilic), 70% biodegradation within 30 days	none
Landfill, anaerobic	ASTM D5526	Concentrated anaerobic inoculum from anaerobic digester plus pre-treated MSW fraction at 35 C, biodegradation time and % reported	none

The market size of bioplastics and biopolymers is expected to grow from its current valuation of around 10.5 billion to a value of 27.9 billion in 2025 (GLOBE NEWSWIRE, 2019). Biodegradable polymers include PLA, PBAT, PHA and TPS. Packaging applications dominate market share of biodegradable plastics, followed by agricultural uses (European Bioplastics, 2020) (**Fig. 6**). Bags for carry-out and biobags used to transport organic waste are included as "flexible packaging" in this data.

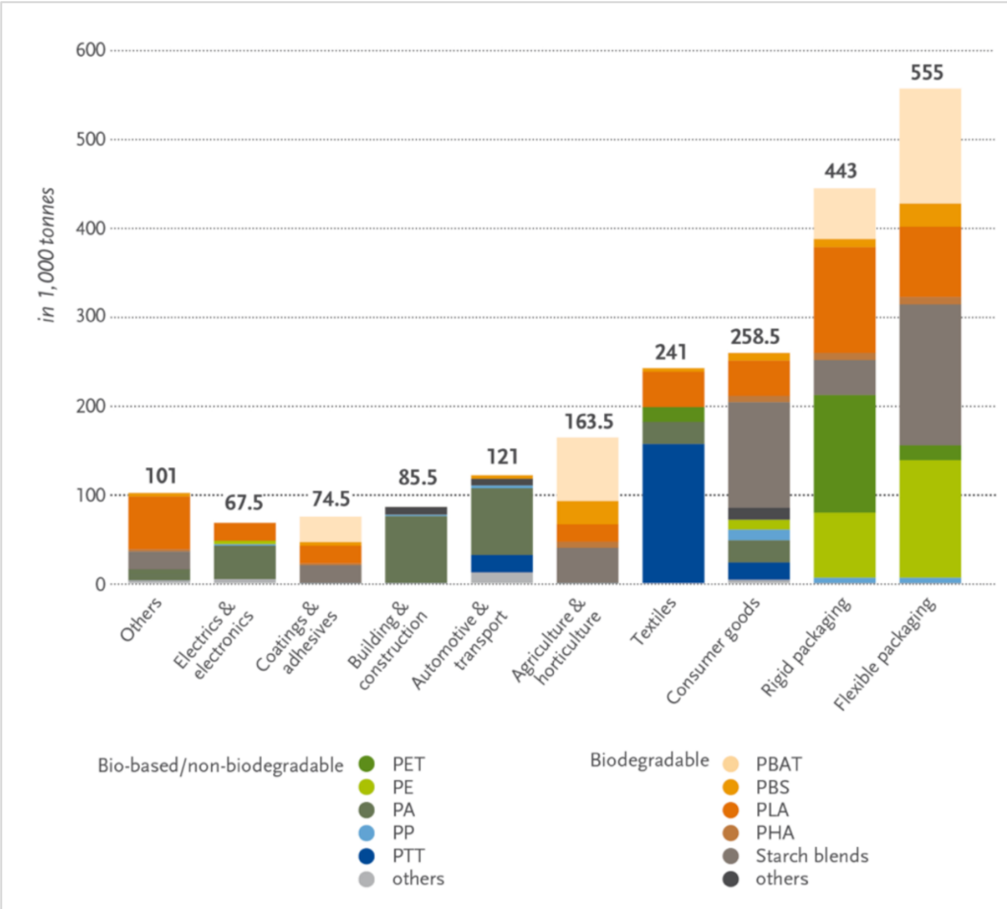

Figure 6: Bioplastic Production Capacities by market segment, 2020
(European Bioplastics, 2020)

2.2 Functionality & Applications of Compostable Plastics in Packaging

Biodegradable plastics exhibit different physical and chemical properties that affect their suitability for packaging applications, and blends are often necessary to create functional materials (**Table 2**). Strength, flexibility, and level of water and oxygen permeability all need to be considered in the design phase (Zhao, Cornish, & Vodovotz, 2020). Design for packaging functionality (shelf life, water resistance) can have tradeoffs with the performance of biodegradable plastics in different degradation pathways and environments. Packaging sectors most commonly targeted for biodegradable and compostable plastics are in food retail and foodservice, although there are instances of other types of packaging being certified as compostable by one or more of the governing bodies responsible, such as mailers for shipping and packaging for other consumer products (cosmetics, décor, etc). Recent BPI guidelines for certification of compostable products indicate that their certification will only be issued or renewed for products that are likely to aid in diversion of other organics to composting (primarily food service and food packaging products); however, European certification standards currently have no similar distinction.

Table 2: Applications of Biodegradable Bioplastics in Food Packaging
(Zhao et al., 2020)

Bioplastic	Packaging items	Manufacturers
PLA	Bottles, cups, trays and packs, films for fresh produce, window for paper bags	NatureWorks, Pyramid, WeForYou, HiSun, PURAC, BIOFRONT
PLA/PHA blends	Coffee capsules, pouches	Ingeo, HiSun, Pyramid, PURAC, BIOFRONT
PLA/PHA/PBAT blends	shopping and waste bags	Ingeo, PURAC, BIOFRONT, HiSun, Pyramid
PLA/cellulose blends	films	FKuR
PBAT	shrink films	BASF
PHA	Bottles, wrappers, straws	Danimer Scientific, RWDC
cellulose	wrapping films and bags for fresh produce and confectionary	Innovia, Futamura
cellulose	metalized cellulose film for snacks	Boulder Canyon, Qualitystreet, Thomton, Futamura
TPS starch blends	films for fresh produce and meat, trays	EverCorn, INC, Novamont, Plantic Technologies
starch blends with PLA/ PHB	blown films	BiologiQ

Polylactic acid (PLA) is the most common biodegradable polymer used in rigid packaging due to its high strength and global manufacturing capacity, but also has applications in films and other flexible packaging types, especially when blended with other biopolymers (European Bioplastics, 2020; Zhao et al., 2020). PLA is bio-based and is most often sourced from corn, sugarcane or other sources of sugar. PLA products resist degradation without elevated temperature and moisture, and are generally not suitable candidates for home composting or degradation in marine or soil environments (Greene, 2018). However, PLA may be blended with fossil-based biopolymers including Polybutyrate Adipate Terephthalate (PBAT) and Polybutylene Succinate (PBS) to enhance degradation. PLA packaging is often transparent, which is functionally useful for many types of packaging (**Fig. 7**).

Figure 7: PLA and PLA blend products

Thermoplastic starch (TPS) is a type of plasticized starch (from potatoes, wheat, or other bio-based sources) often used in films or other flexible packaging applications; however, TPS is highly sensitive to moisture, has high viscosity and high tendency to biodegradation, limiting its functionality (Bátori et al., 2018). Many commercially available TPS packaging types include blends with PLA, PHA or other polymers (Zhao et al., 2020). Novamont's TPS-based Mater-Bi® is often used for compostable bin liners and bags for produce or carry-out (**Fig. 8**), and is suitable for home composting and certified as TUV OK biodegradable MARINE and SOIL.

Figure 8: Mater-Bi bags

Polyhydroxyalkanoates (PHAs) are a family of bio-based polymers produced through fermentation and only make up a small fraction of biodegradable packaging current production capacity. However, PHA packaging use is projected to grow significantly as manufacturers of PHA have been tapped by large food packaging companies including Nestle and Mars in development of new packaging materials (Goldsberry, 2021; Peters, 2020). PHA is highly biodegradable and PHA straws are already commercially available (**Fig. 9**).

Figure 9: PHA straws and bottles
(bottles not yet commercially available)

2.3 Life Cycle Assessment of Compostable Packaging

Life Cycle Assessment (LCA) is a methodology used in both academic and industrial research for assessment and comparison of environmental impacts stemming from the entire life cycle of processes and products. LCA can be used to account for upstream, accompanying and downstream processes or products that enable a product or service. International standards have been developed which govern the general requirements for LCA construction and interpretation (Finkbeiner, Inaba, Tan, Christiansen, & Klüppel, 2006). LCA is often used to assess the environmental impacts of consumer products and is increasingly employed when evaluating packaging materials, especially when comparing two material options (Franklin Associates, 2018; Vendries et al., 2020). Important components of an LCA are definition of goal and scope, gathering of inventory data, and choice of impact categories**.** Inventory data includes emissions to air and water as well as use of resources and energy, and is translated into impact categories with the use of Life Cycle Impact Assessment (LCIA) methods. LCIA translate these energy, material and waste flows to particular impacts – common impact categories shared among LCIA methods include climate change, fossil and metal resource depletion, land use and ecotoxicity.

Product, plastic, or polymer-level LCA can be termed “cradle-to-gate” if the scope is limited to examination of production processes and material use. For fossil-based plastics, this raw material input primarily consists of byproducts from the oil and natural gas industries, whereas for bio-based plastics these inputs can come from various sources of biomass including crops grown specifically for plastic production or in some cases, byproducts of other industrial applications (**Fig. 10**). As bioplastic manufacturing has grown, LCA has often been used to evaluate the environmental impacts of production and use of bioplastic products including packaging. PLA has been a large focus in LCA work due to its high market penetration among the class of biodegradable bioplastics, and is generally found to have lower greenhouse gas emissions associated with its production when compared to fossil-based counterparts, but often shows higher impacts in terms of land use change and eutrophication potential (Spierling et al., 2020; Vink & Davies, 2015). LCA has been used to examine production and use of PLA blends and other bioplastic packaging in grocery retail (Abejón, Bala, Vázquez-Rowe, Aldaco, & Fullana-i-Palmer, 2020), disposable coffee pods (Kooduvalli, Vaidya, & Ozcan, 2020) and take-out cups (Häkkinen & Vares, 2010), among others. LCA of bioplastic packaging types can vary widely depending on feedstock sourcing and functional blending with multiple polymer types, as well as choice of impact categories.

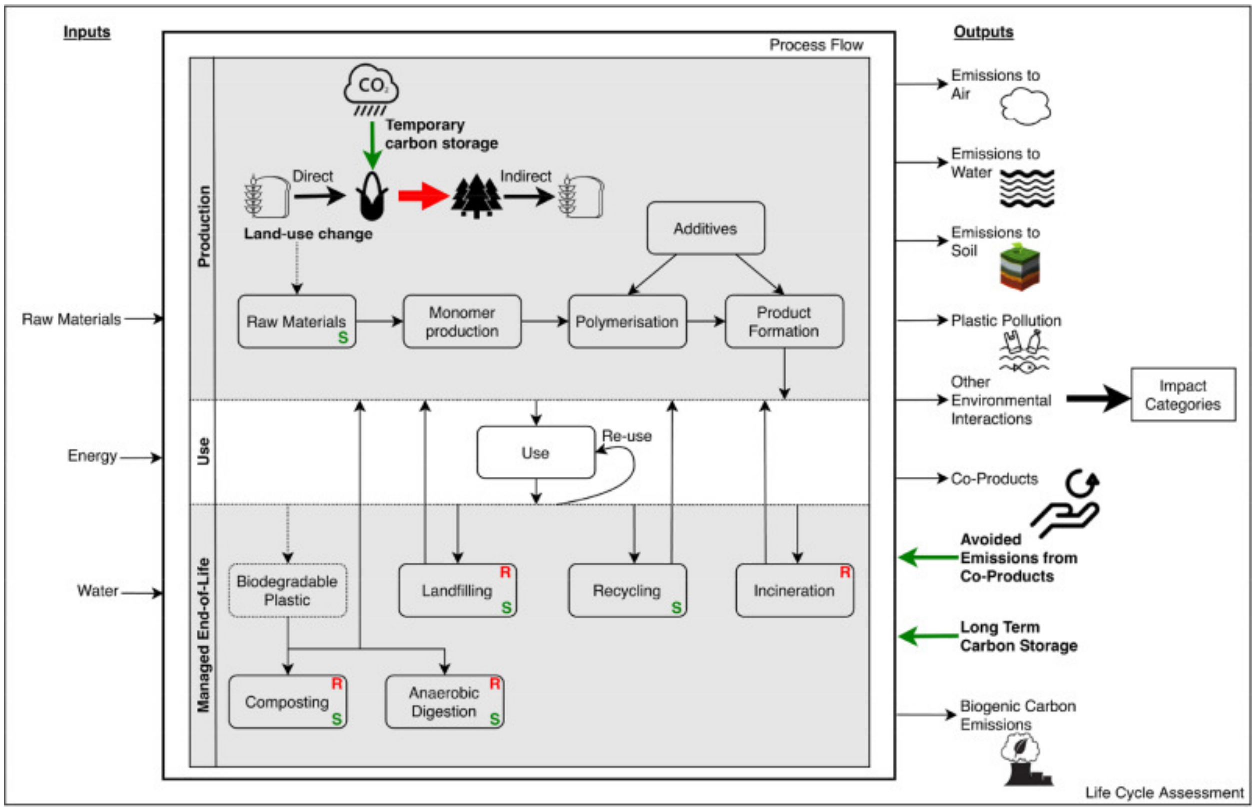

Figure 10: Typical system boundaries for bio-based bioplastic value chains
(Bishop, Styles, & Lens, 2021)

2.3.1 EOL in LCA

Not all packaging and plastics LCAs include end-of-life (EOL) within their scope. Cradle-to-gate boundaries are appropriate when focus is on examination of raw material extraction (e.g. agriculture, mining) and manufacturing processes (e.g. pulping, thermoforming) (Tsiropoulos et al., 2015; Yates & Barlow, 2013). There is often scrutiny focused on sourcing of bio-based feedstocks and associated impacts from irrigation, fertilizer and land use (Brizga, Hubacek, & Feng, 2020; Walker & Rothman, 2020). When EOL is considered for packaging materials, methodological choices can largely shape the outcome of analysis. Ideally, EOL treatment in LCA should be realistic in order to avoid bias and present realistic comparison or consideration of both benefits and drawbacks to bioplastics (Bishop et al., 2021). However, few LCAs that consider EOL of bioplastics reflect a North American context, and studies that do consider EOL have inconsistent accounting of waste management infrastructure, carbon sequestration and biodegradation (Bishop et al., 2021; Spierling et al., 2020). Further discussion of the existing literature can be found in **Chapter 4**, following background on composting infrastructure in the United States in **Chapter 3**.

CHAPTER 3: COMPOSTING IN THE UNITED STATES

Composting as a form of management for municipal solid waste (MSW) emerged in the United States with the increased involvement of government in regulation of solid waste activities and the passage of the Resource Conservation and Recovery Act (RCRA) in 1976. RCRA was designed to bring central oversight to reduction of external costs of open dumping, burning and poorly designed landfills. Increased concern over landfill space and value of diversion led to the passage of some of the first landfill bans for yard trimmings in the 1980s and 1990s (Nora Goldstein, 2001), and many municipal utilities soon saw the value of biosolids composting amended by these materials. Some of the first centralized composting facilities designed for MSW containing mixed organics and food waste were also established during this time period (Nora Goldstein, 2001). Recent growth in composting infrastructure has been aided by a growing number of favorable state and local regulations concerning waste measurement, diversion and greenhouse gas implications of organic waste disposal.

National landfill diversion of MSW by composting and other methods is monitored by the EPA; however, tonnage of composted materials is only monitored for food and yard trimmings, measured by reporting of states and other estimates (**Table 3**). EPA estimates show that more than half of food waste generated in 2018 was landfilled. Estimation of packaging material wastes (paperboard, compostable plastics) managed through composting has not been undertaken by the EPA on a national level – measurement is inconsistent and volume is assumed to be low. In a properly managed composting operation and management system, these packaging material types should only constitute a small portion of the organic material that is managed.

Table 3: Food Waste and Yard Trimmings, Composted and Landfilled, 2018*
(U.S. EPA, 2020)

	thousand tons	**pounds per person per day**	**% of material generation**
Food - Composted	2,590	0.04	4.1%
Yard Trimmings - Composted	22300	0.37	63%
Total - composted	**24890**	**0.42**	**24.3%**
Food - Landfilled	35280	0.59	56%
Yard Trimmings - Landfilled	**10530**	0.18	30%
Total - Landfilled	**45810**	**0.77**	**46%**

*Other management pathways not accounted for in this table are combustion (both food and yard), and specific to food – donation, animal feed, biochemical processing, anaerobic digestion, sewer treatment and land application

Composting is often used to manage and treat materials that are not usually included in definitions of municipal solid waste. Types of organic wastes that are not usually included in definitions of MSW but often play an important role in the business models and operations of composting operations are listed in **Table 4**. Composters who operate outside of the MSW sector may not always be interested in working with MSW generators and haulers. Altering their business model to incorporate MSW often involves consideration of increased operational capacity needed to deal with contamination from these incoming feedstock streams. However, municipalities can find willing partners in agricultural operations or municipal wastewater facilities given the right combination of location, feedstock quality guarantees and demand for finished soil amendment products.

Table 4: Sources of Organic Wastes for Composting
(Bernal et al., 2017), (Platt, 2014)

Municipal Waste	Residential, commercial and institutional wastes: Yard trimmings, pre-consumer food waste (e.g. food retail spoilage), post-consumer food scraps, paper, wood
Industrial byproducts or wastes	material from food and beverage industry – spent brewer's grains, scraps from food processing (e.g. meat scraps, cheese whey, culled potatoes), pre-consumer food waste not destined for retail; C&D wood waste, other organic industrial liquid wastes

Agriculture	Livestock manure, chicken litter, crop residue (e.g. corn stover, wheat straw, hemp stalks), hay and bedding
Wastewater treatment	Municipal biosolids, sludge from biological treatment of wastewater
Forestry	Bark residue, leaves, wood residue

3.1 Composting Operations

A large list of composting facilities was gathered through a desktop survey sourced from state permitting agencies, previously published datasets (*Composting Facilities, US and Territories, 2020, EPA Region 9*, 2020), web research and input from composting professionals. A number of data points were targeted for collection, with a focus on determination of feedstocks regularly accepted and whether these feedstocks included Municipal Solid Waste. Special focus was given to those facilities that were permitted for some form of food waste composting or were indicated to accept food waste by some other source. Other data points targeted where possible included ownership type (private/commercial, public/municipal, institutional or other), composting technology used and yearly tonnage or cubic yards processed, as well as information on what compostable items are accepted if indicated.

After initial data gathering, a number of categories were determined to be a useful descriptor of the overarching business models and operational specialties of composting facilities (**Table 5**). Due to the diversity of composting operations, differences in data sources by state, and large dataset, there is some overlap in categories; however, differentiation of categories is useful to avoid comparison of composting operations that are not directly comparable (e.g. universities and industrial waste processing facilities) (**Fig. 11**).

Table 5: Initial Categories of Composting Operations

Largely Private/ Commercial	Industrial	Commercial facility that deals with organic industrial wastes that are almost exclusively non-MSW waste. Food processing waste, wood product waste, C&D waste, industrial wastewater
	MSW Hauler & Processor (all)	Waste management facility operated by commercial hauler that also operates landfill(s) and/or MRF(s) in addition to organics composting

	Agricultural Products	Commercial operation focused on business relationships with agricultural operations in feedstock (manure, crop residuals, hay, other farm waste) and/or finished product (sell bulk to agricultural operations, nurseries). Some of these facilities may also accept MSW from municipalities or other business partners, especially when located near metro areas
	Landscaping	Majority of business partners are landscapers, land clearing and tree trimming; focus may be on mulching etc but operates under composting permit. Municipal yard trimmings, non-MSW waste from forestry and C&D
	Community Compost	Focused on diverting food scraps from residential and commercial customers in a given region, usually a group of counties or cities. May be nonprofit or commercial, may partner with municipalities for customer base
Largely Public/ Municipal	WWTP	Municipal water treatment or water reclamation facility
	Municipality solid waste	Municipally owned or contracted facility that primarily works with municipal generators. Often public/private partnership
Institutional	Farm	co-located with farming operations. Some may accept waste from offsite MSW partners; some overlap with Agricultural Products
	College/University	Generally only compost waste generated onsite, but may have community partners
	Correctional	Generally only compost waste generated onsite, but may have community partners
	Military	Generally only compost waste generated onsite, but may have community partners
	Community Garden	Network of community garden composters or stand-alone
	Institutional	Other institution (ex. Zoo, corporate campus)

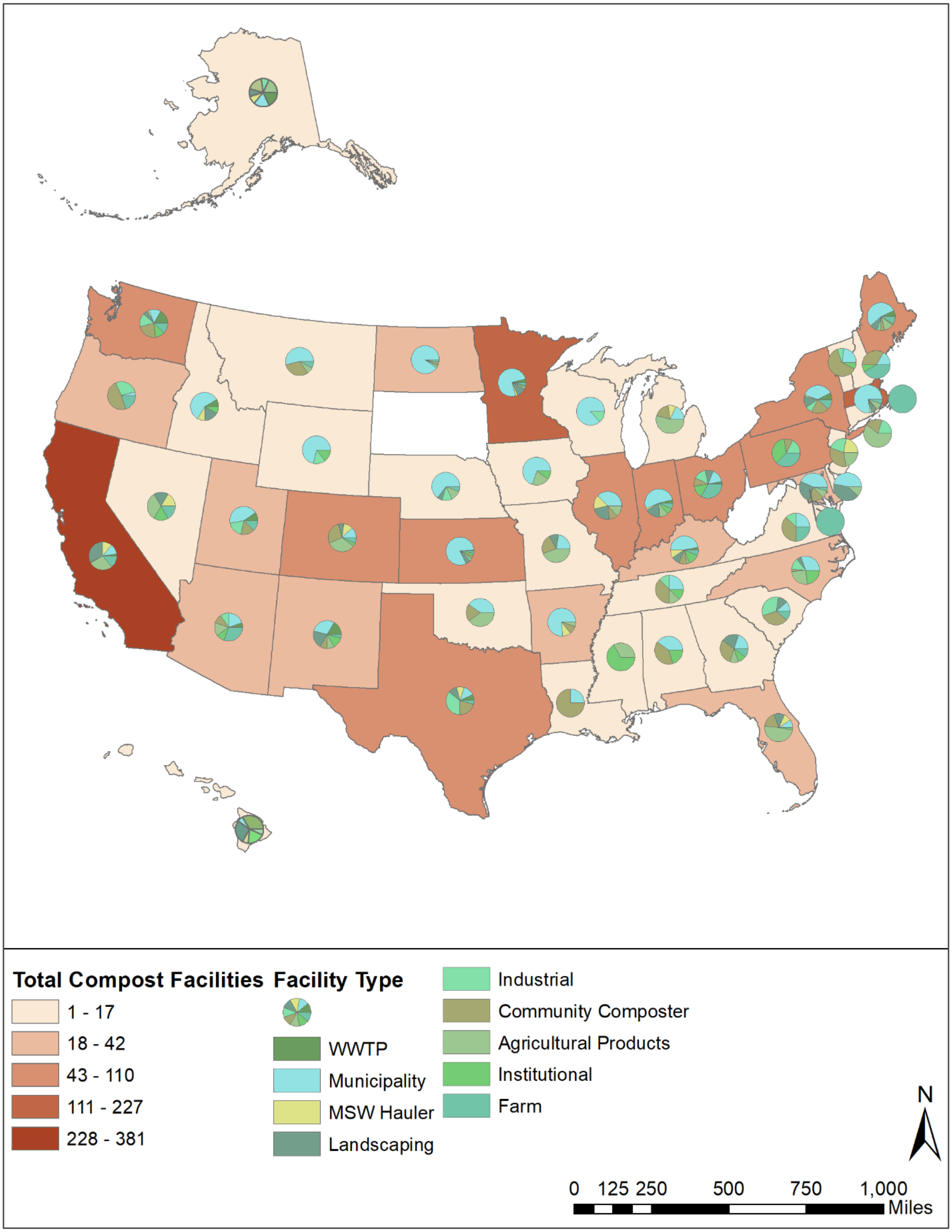

Figure 11: Composters by Type
No data available for North Dakota and West Virginia

Many municipal composting operations only accept yard trimmings from residents, such as limbs, leaves and grass. These facilities are common in states with yard trimmings landfill bans that mandate diversion and beneficial use. While augmenting these facilities to accept other organics such as food waste can save additional landfill space, it requires significant investment in planning and education. Introduction of food waste may create odor and attract pests, which can present a large barrier for facilities that are located near residential zones (E. M. Christensen, 2009). The presence of this existing infrastructure for organics diversion in combination with regulation and policy that prioritizes waste diversion from landfill make it more likely that a municipality will offer some form of food waste composting (Pollans, Krones, & Ben-Joseph, 2017).

A growing number of states and some cities have implemented additional landfill bans or mandatory diversion mandates for food waste. These mandates can boost investment in centralized collection and organics recycling infrastructure including both composting and anaerobic digestion. However, the scope of these regulations varies. Most only apply to large commercial generators over a certain threshold of waste generation. Some only mandate diversion for these generators if a composting facility already exists in their area. However, the most sweeping mandates require both residential and commercial generators to divert food waste from landfill (Vermont, California).

In the absence of centralized management strategy and large facilities to manage food waste through composting with other organics, many small-scale composting operations have adopted a more community-focused approach to food waste collection and management. So-called “micro-haulers” service neighborhoods and cities with voluntary curbside service and often partner with community gardens or networks of community gardens to ensure that finished compost is used for local food production and education. Current counts of community composting operations in the U.S. put the number at more than 200 (Lindsay, 2020).

Feedstocks accepted by composting facilities were also condensed into categories consistent with past data gathered by BioCycle for ease of comparison and consolidation: Yard Trimmings, Agricultural Wastes, Biosolids, Septage, MRF-processed or unsorted MSW, Vegetative Food Waste, All Food Waste, Pre-consumer Food Waste, Pre- and Post-Consumer Food Waste, Food-soiled paper, Compostable Products

3.2 Organics Hauling and Collection

There are a variety of modes of collection that are used for organic wastes, depending on the setting and the scale of organic waste disposal operations. Haulers that only collect yard trimmings may only do so seasonally and may not distribute any special collection containers for their customers; however, if food waste is included in curbside service containers are necessary. Municipalities that have supported mandatory composting will often have frequent curbside collection for customers using collection vehicles similar to those used for trash and recycling, with lifting arms for emptying bins. These vehicles may also need to be augmented to deal with heavy, wet food waste and ensure minimal leakage. Smaller-scale collections efforts (e.g. pilot-scale, limited subscription service) may collect bins or pails in trucks, vans or even by bicycle. Customers that do not have curbside organics collection may have the option of dropping off their organics at a transfer station, farmers market or other designated location or may participate in a community gardening initiative that accepts food scraps for composting.

3.3 Composter acceptance of compostable packaging

Composters who were expected to accept food waste based upon their permitting type, web search and past research by composting stakeholders were targeted for a survey regarding their operations in more detail including information on food waste generators that they work with and confirmation of feedstocks accepted. Surveys were first distributed by email where contact information was available and Survey123 through ArcGIS online was used for survey distribution. After reminders to complete the survey via email, facilities were contacted by phone. While initial outreach was blanketed to all food waste facilities including institutional and community composters included in initial data collection, follow up prioritized larger facilities (**Fig. 12**). A number of composters indicated that the food waste generators that they work with were limited to food processing facilities or small amount of pre-consumer food waste, or they do not accept food waste. The level of detail for information gathered over the phone was sometimes limited by the level of knowledge of facility staff on overall operations. Survey can be found in Appendix A-1.

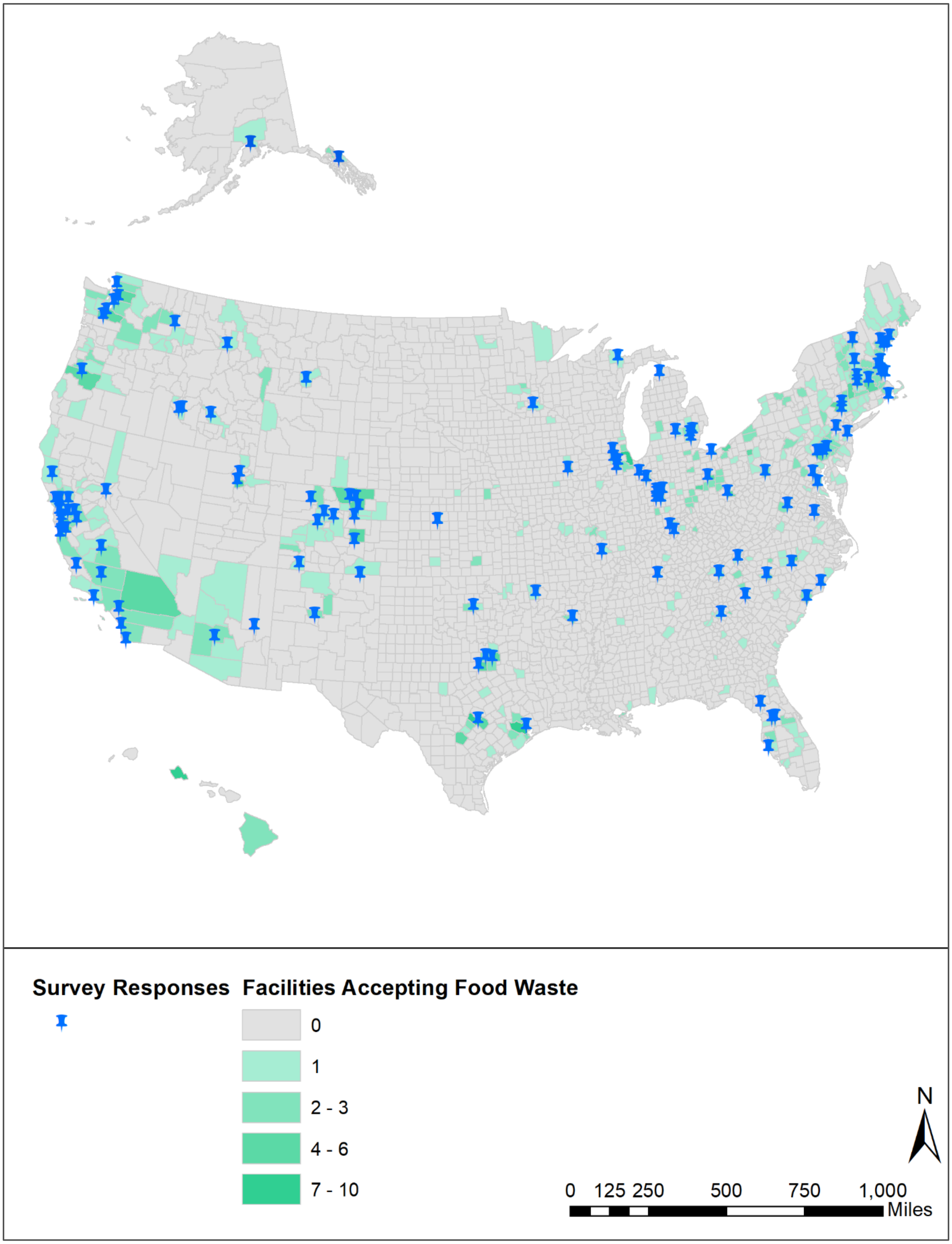

Figure 12: Survey Responses
(n = 129)

When applicable, composters were asked a number of open-ended questions regarding their perceptions of compostable packaging, how new compostable packaging materials are addressed and how introduction of post-consumer packaging and foodservice ware affects their operations. Answers to these open-ended questions illuminated a number of themes (**Fig. 13**).

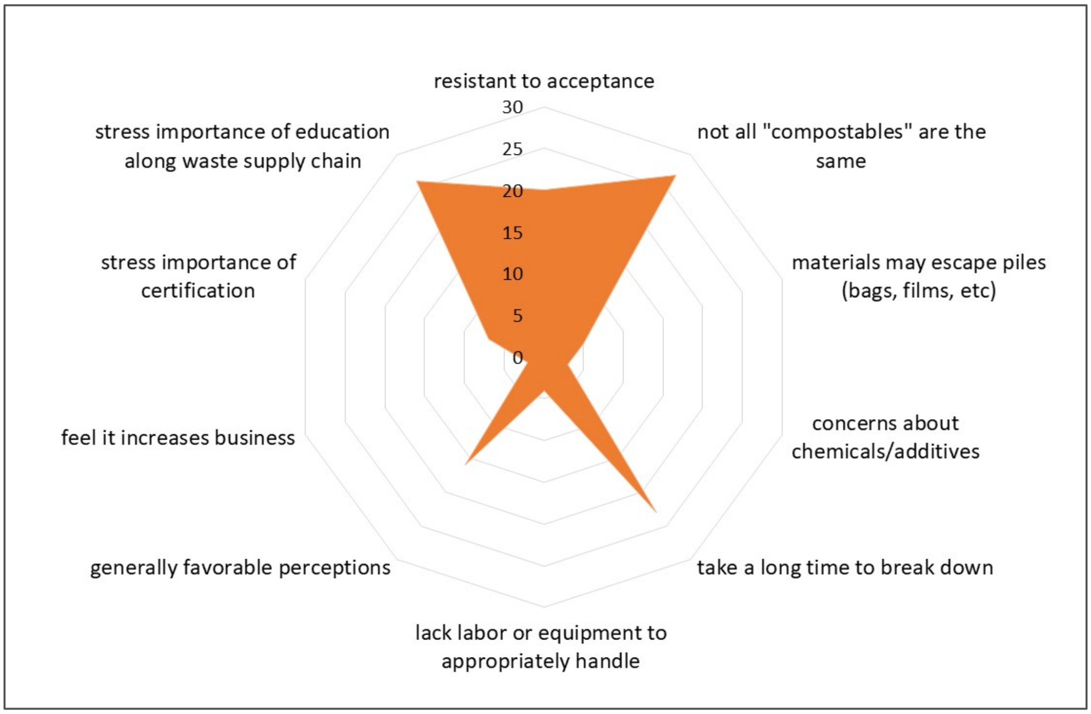

Figure 13: Spider graph for themes addressed in composter survey answers
Number of times that the following themes were mentioned in response to question regarding general perceptions of compostable packaging. Answers varied in length and some answers touched upon more than one theme (n = 65)

Many composters are resistant to incorporation of any compostable products into their piles. Their perceptions of compostable packaging and products, even when certified, has been shaded by negative past experiences. Those who had negative experiences often mentioned the greenwashing of products and the difficulty of education of generators that they work with. Confusion is introduced when they have too many rules about labels and lookalike products – it is more efficient to tell all generators to avoid putting any of these products in the bin and have all potential contaminants removed up-front. In addition, composters who wish to have their product certified by OMRI for use on organic farms (which fetches a high price) by rule cannot accept compostable packaging materials as they are “chemically modified.” These composters will advise their business partners not to include compostable packaging and if seen, will treat it as contamination and remove it.

Interestingly, a few composters who did not indicate acceptance of compostable plastics and remove them as contaminants still indicated that they are supportive of the work of BPI in publicizing certified compostable products as they feel it has increased consumer awareness of composting overall and indirectly helps the growth of their business. All composters who accept compostable products and do not remove it before processing stressed the importance of education along the “waste supply chain.” If possible, many composters work closely with haulers and generators on selection of compostable products used and will advise them on those that they have vetted. Loads that contain large amounts of compostable plastics and packaging without the valuable nutrients from food scraps are not valuable to composters.

Most composters only accept materials that are certified by one of the governing bodies specific to industrial or home composting (**Table 1)**. These certifications are an important first step in ensuring that the material is not going to negatively affect the quality of their finished product as the certification often includes tests for PFAS and other harmful chemical additives. The most-mentioned certifications or labels that composters seek out are BPI, ASTM 6400, and CMA (**Fig. 14a**). There is some lingering mistrust of compostable products that are fiber-based as many of these products were found to have PFAS in recent years. In addition to looking for certifications, composters often conduct initial field tests or trials to determine how new products perform in their piles (**Fig. 14b**).

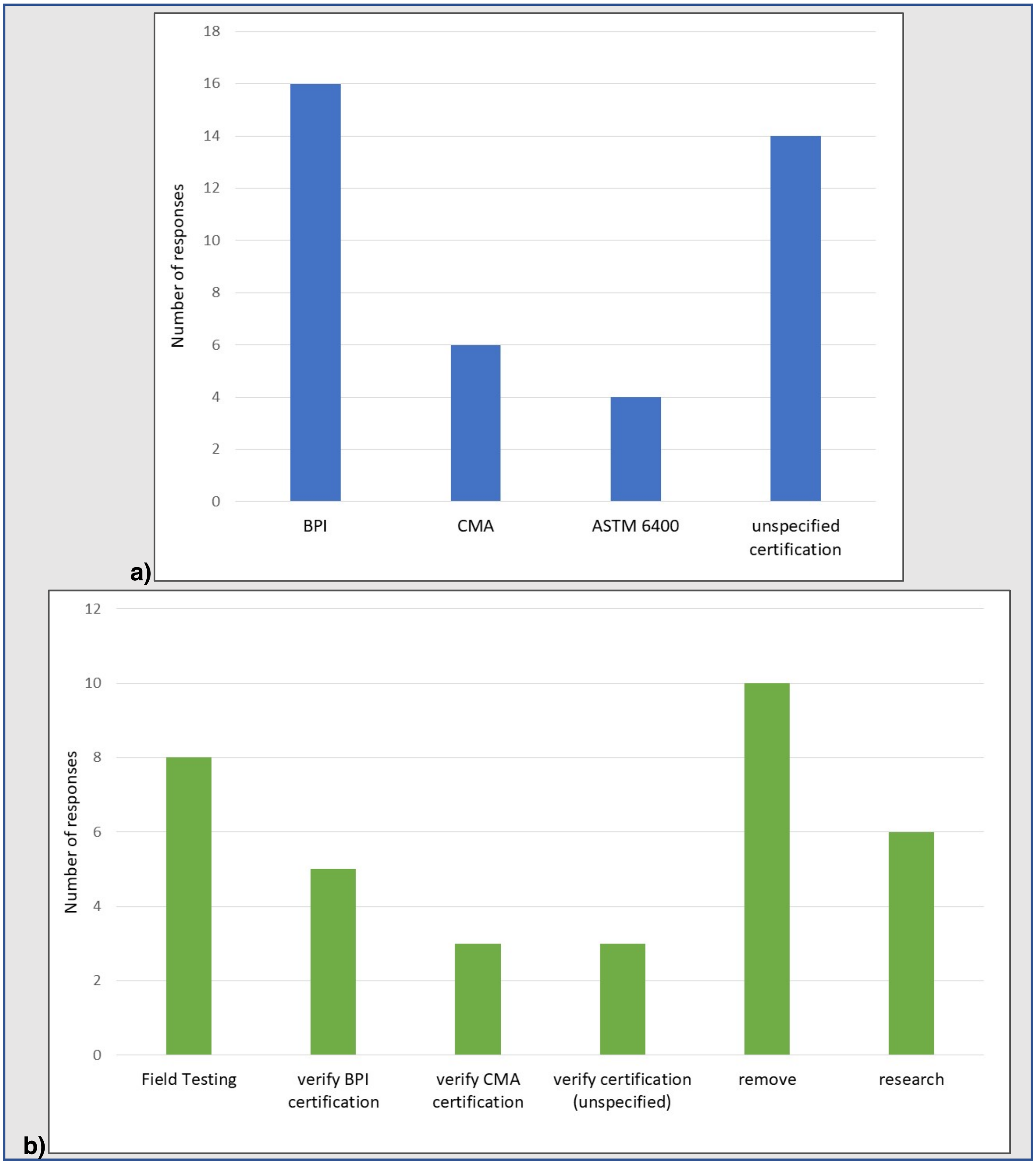

Figure 14: Responses to composter survey questions on compostable packaging acceptance

a) Number of responses that mentioned certifications in response to questions regarding what specifications packaging needs to meet for facility acceptance and which certifications are important to them; b) Number of responses that mentioned the following when asked how new materials are addressed

CHAPTER 4: LITERATURE REVIEW

4.1 EOL in LCA of biodegradable packaging materials

4.1.1 Composting

In properly controlled aerobic composting, carbon in organic materials is emitted as carbon dioxide and a proportion is stored in the finished compost – very little should generate methane; however, anaerobic pockets can persist in compost piles without proper aeration and porosity and generate trace amounts of these more potent greenhouse gases (Hermann, Debeer, De Wilde, Blok, & Patel, 2011).

Composting of bioplastics and other carbon-rich organic materials is not possible without other organic components with high nutrient content, such as food scraps and green waste. There are a number of approaches to assigning credit for compost produced from management of organic waste components. Some compostable plastic LCA simply allocates composting of different waste material fractions by mass and assumes that all compost replaces synthetic fertilizer in land application (Vink & Davies, 2015). Others differentiate between nutrient-rich organic wastes and biopolymers, which do not generally contain any nutrients that would displace synthetic fertilizer products (Hottle, Bilec, & Landis, 2017). While compostable bioplastics do not contribute nutrient content, they may aid in composting piles as a bulking agent and enable increased food waste capture by composters (Compost Manufacturing Alliance LLC, 2018). So-called system approaches consider biopolymers or other carbon-rich and nutrient-poor materials as part of a composting mix and assign part of the benefit of compost land application to the end-of-life of that material, but assign greater value to nutrient-rich components such as food waste (Hermann et al., 2011). Other emissions associated with composting of nutrient-rich components include nitrogen gas, ammonia, and VOCs that cause odor.

4.1.2 Landfilling

Organic solid waste produces landfill gas (LFG), a mix of carbon dioxide, methane and other trace gases including nitrogen when subjected to the anaerobic conditions of municipal solid waste landfills (**Fig. 15**). Models such as the U.S. EPA's Landfill Gas Emissions Model (LandGEM) utilize first-order decay to estimate generation of LFG, and LandGEM is the mostly widely used basis for regulatory estimation and compliance (Alexander, 2005). Emissions from operation of landfill can be assigned to a particular waste stream component in LCA based upon some combination of its mass, volume, and chemical composition depending upon the level of detail in the landfill model.

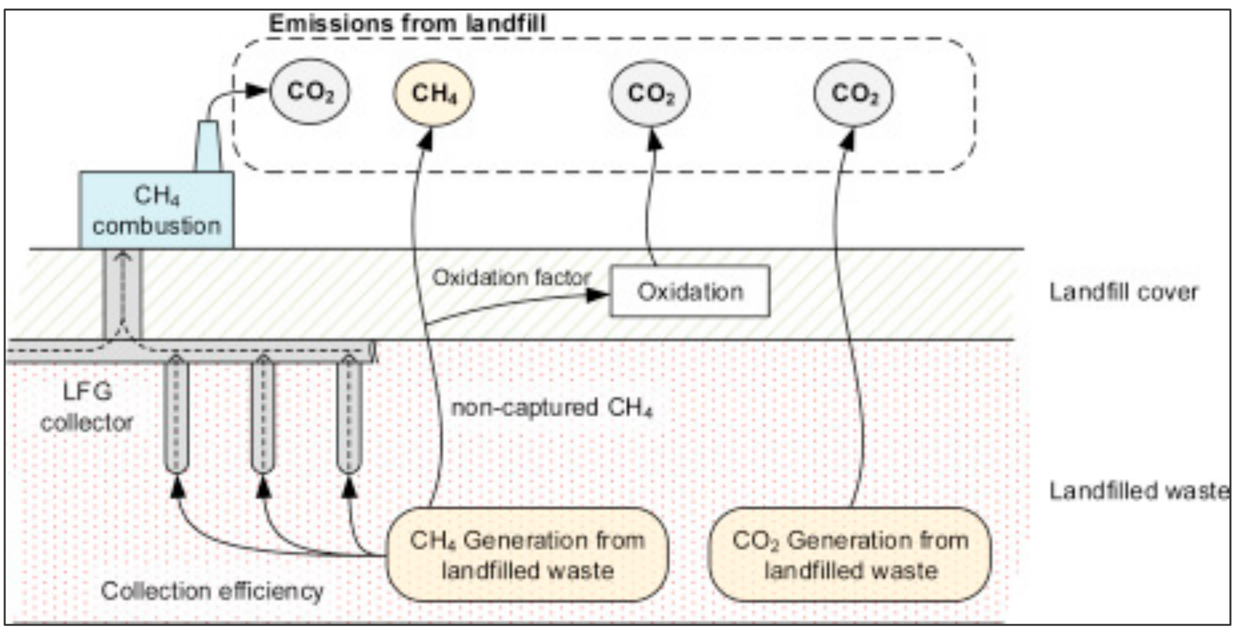

Figure 15: LFG emissions generated from landfilled organic waste
(U. Lee, Han, & Wang, 2017)

Inert, inorganic materials do not degrade in landfill conditions typical to the United States, and most plastic waste is sequestered when landfilled. Non-biodegradable plastics can therefore be treated as carbon sinks when buried in the landfill; however, due to their persistence they do have other impacts upon operations - they take up space and chemical additives may result in some emissions via leachate. In some cases biodegradable plastics such as PLA are also assumed by LCA practitioners to resist degradation in landfill (Vink & Davies, 2015); however, this assumption has been challenged by solid waste research simulating high-temperature conditions often found in landfills in the United States (Krause & Townsend, 2016).

Landfill operators often collect LFG for flaring or electricity generation, and different waste fractions may be credited for regional electricity offset by this use in LCA. Collection efficiency is determined by the configuration of cells, waste decay speed and type of LFG collector (U. Lee et al., 2017). For organic materials such as food waste and biodegradable bioplastics, higher decay rates may result in a portion of LFG escaping before a cell is capped and the LFG can be captured (Levis & Barlaz, 2011). For bio-based plastics, carbon dioxide that is emitted as this material degrades is often accounted for differently than that of fossil-based plastics, as the carbon in this material is biogenic – and may be considered “carbon neutral”. However, methane generated has a much larger global warming potential (GWP).

4.1.3 Recycling

There are several methods used in LCA to account for recycling material after use, and “crediting” a material for the reduced energy and inputs of recycled material when compared to virgin material (van der Harst, Potting, & Kroeze, 2016).

Biodegradable plastics are not often recycled – while PLA is technically recyclable, no infrastructure exists on a large scale to facilitate this recycling (Alaerts, Augustinus, & Van Acker, 2018). Furthermore, attempts to introduce biodegradable plastics into existing recycling systems could create problems as biodegradable plastic products may not be easily discernable from plastics such as PET and may negatively impact the value of recycled PET if introduced in excess (Alaerts et al., 2018). However, existing LCA of PLA and TPS in a European context has considered this option for EOL (Spierling et al., 2020; Yates & Barlow, 2013).

4.1.4 Littering and Mismanagement

Existing LCA frameworks rarely include potential effects of mismanagement or littering of packaging materials (Bishop et al., 2021). However, there is increasing interest in including some form of persistent litter as an indicator within LCA, and to quantify the effects that this has on human health, ecosystems and socio-economic assets (Verones, 2020). While the science on these effects is still developing, some LCA practitioners have begun adding midpoint indicators that attempt to represent some of the risks that littered plastic waste pose. Added midpoint indicators include persistence in the environment, based upon evidence from similar product and material types (Russo, Stafford, & Nahman, 2020), and a "littering indicator" based upon the probability of abandonment by consumers and the persistence of plastic products in the environment (Civancik-Uslu, Puig, Hauschild, & Fullana-i-Palmer, 2019). Both of these indicators include consideration of biodegradation potential in varying natural environments.

4.2 Waste LCA

Stakeholders in packaged goods are increasingly interested in the end-of-life destinations for their products; however, they often have little control over operations of the municipal solid waste management systems that handle the majority of packaging waste. Solid waste management systems in the United States are largely controlled at the municipal – city and county – level rather than by states or the federal government. Because of this, system components, from mode of collection to landfill and recycling technology, can vary in different geographies.

Policy makers involved in local solid waste management often emphasize goals around waste reduction, landfill diversion and recycling (Silva, Rosano, Stocker, & Gorissen, 2017). However, simple statistics about landfill diversion and recycling may not paint a complete picture of the full Municipal Solid Waste (MSW) system along with environmental and economic considerations. Life cycle impacts that detail effects of recycling including offsetting virgin material production, as well as the impacts of waste collection fleet technologies and regional economies can play a meaningful role in assessing optimal management (Anshassi, Laux, & Townsend, 2018).

LCA has been employed extensively to study municipal solid waste systems (T. H. Christensen et al., 2020; Khandelwal, Dhar, Thalla, & Kumar, 2019). Common processes included in LCA of MSW systems include collection, transport, recycling, landfilling and composting, as well as auxiliary processes and capital infrastructure needed for all of these components (**Fig 16**). Waste LCA can be used to examine existing waste management infrastructure configurations (Edwards, Othman, Crossin, & Burn, 2018; Fernández-Braña, Feijoo-Costa, & Dias-Ferreira, 2019; Franchetti & Kilaru, 2012; Saer, Lansing, Davitt, & Graves, 2013), or to assess potential impacts of changes to MSW infrastructure (Coventry, Tize, & Karunanithi, 2016; Guven, Wang, & Eriksson, 2019; Righi, Oliviero, Pedrini, Buscaroli, & Della Casa, 2013).

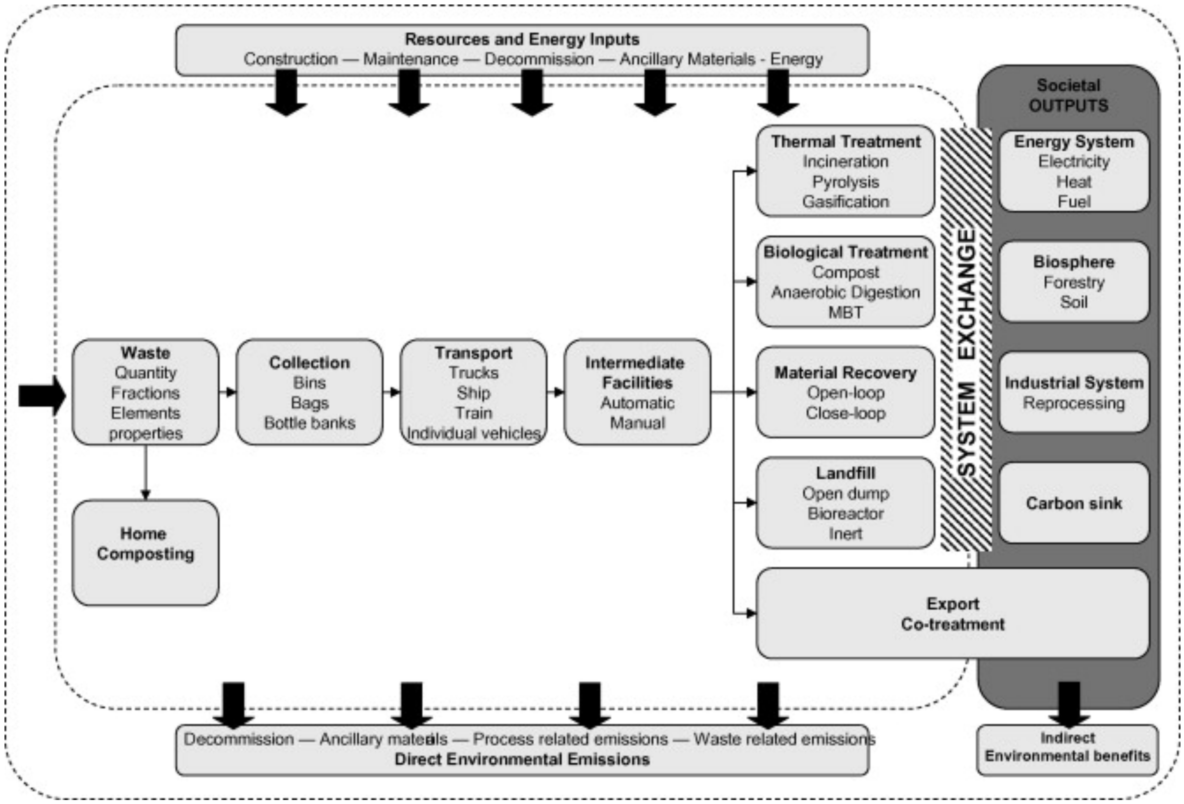

Figure 16: Generic integrated waste management system
(Gentil et al., 2010). The outer dotted line represents society at large (earth system and technosphere). The inner dotted line represents the waste management systems represented by a number of waste management technologies (light shaded grey). The dark shaded grey represents the inputs and the outputs of the whole waste management system. The box indicating the system exchange shows the relationships of materials and energy flows between the waste industry and wider society, through substitution.

4.2.1 Life Cycle Costing

Life Cycle Costing (LCC) is often undertaken alongside LCA to incorporate economic considerations in the analysis and comparison of scenarios, products or strategies (Martinez-Sanchez, Kromann, & Astrup, 2015). It can also be undertaken separately (apart from LCA) as a comprehensive strategy to evaluate costs and benefits to any system change. LCC has been applied to evaluation of different types of food waste recycling and plastic waste management in Korea and Denmark (Faraca, Martinez-Sanchez, & Astrup, 2019; K. H. Lee, Oh, Chu, Kwon, & Yoo, 2017). LCC alongside LCA allows stakeholders to examine costs associated with scenarios that are also evaluated on the basis of environmental impacts.

There are 2 different types of costs that are often accounted for using LCC: Internal costs and External costs. Social Cost refers to the sum of both. When applied to waste management, social cost is understood as society's cost to process waste, and is the sum of external and internal costs (Martinez-Sanchez et al., 2015). Common costs incurred by waste management stakeholders can be assigned to these categories (**Table 6**).

Table 6: Summary of costs incurred by waste management stakeholders and categorization into internal, external and social costs
(Martinez-Sanchez et al., 2015)

<table>
<tr><th></th><th>Internal costs</th><th>External costs</th><th>Social costs</th></tr>
<tr><td>Incurred by</td><td>Waste agents (e.g. waste generator and operators)</td><td>All the members of society</td><td>Society</td></tr>
<tr><td>Budget cost</td><td>-Bags
-Bins
-Capital goods
-Materials and energy consumption
-Labor costs
-Material and energy sales</td><td></td><td rowspan="2">Sum of internal costs (excluding transfers) and external costs for society (i.e. waste generator, waste operator and other agents)</td></tr>
<tr><td>Externalities cost</td><td></td><td>-Time consumption to source separate
-Health issues
-Disamenities
-Working environment issues</td></tr>
<tr><td>Transfers</td><td>-Fees
-Taxes
-Pecuniary externalities*</td><td></td><td>Not applicable</td></tr>
</table>

4.2.2 MSW modeling tools

Some aspects of LCC are often incorporated into the economic modeling capabilities of municipal solid waste decision tools that assess life cycle impacts. Models and decision-making tools specific to solid waste management can help stakeholders evaluate economic, environmental and social impacts of existing and proposed solid waste management system configurations, and highlight the impact of alternative treatment for specific waste stream components (Gentil et al., 2010).

The Solid Waste Optimization Life-cycle Framework (SWOLF) allows users to optimize municipal solid waste management strategies through examination of both cost and environmental impact, and has been used to examine different strategies for landfill diversion and cost minimization, especially focused on municipal government policy prioritization (Jaunich, Levis, DeCarolis, Barlaz, & Ranjithan, 2019; Levis, Barlaz, DeCarolis, & Ranjithan, 2014).

The Waste Reduction Model (WARM) and Municipal Solid Waste Decision Support Tool (MSW-DST) were both developed with a focus on the United States, and incorporate both LCA and LCC. WARM is a greenhouse gas accounting tool that accounts for upstream processes such as raw material extraction and manufacturing when generating impact assessments for reduction and recycling. WARM reports MSW management scenario impacts in terms of carbon dioxide-equivalents, energy use, labor hours, wages and taxes (U.S. EPA, 2019). MSW-DST is similar in functionality but allows for multiple environmental indicators including ecotoxicity, climate change and depletion of nonrenewable resources, as well as costs for collection and treatment facility operations (Thorneloe, Weitz, & Jambeck, 2007). MSW-DST utilizes SWOLF for modeling functions. Both were developed with a focus on MSW system operators and include a number of individual waste stream components and customizable options; however, these models do not currently have inventories that reflect management pathways for biodegradable plastics that are the focus of this project. In addition, the ability to ascertain the influence of individual components of the MSW system on results can be limited (Gentil et al., 2010).

Modeling tools that allow separation and allocation of the impacts of MSW management to specific waste stream components include Environmental Assessment System for Environmental TECHnologies (EASETECH)(formerly EASEWASTE) (Kirkeby, Birgisdottir, Bhander, Hauschild, & Christensen, 2007). EASETECH is also highly customizable and can incorporate data from common LCI libraries such as ecoinvent along with specialized modeling capabilities for municipal solid waste operations including mass balancing across the management chain and allocation by mass or economic value. EASETECH has been used to compare management scenarios for multiple waste fractions including organic waste and plastics (Manfredi, Tonini, & Christensen, 2011; Rigamonti et al., 2014).

CHAPTER 5: COMPOSTABLE PACKAGING WASTE MANAGEMENT IN THE SOUTHEASTERN UNITED STATES

5.1 Landfilling

Landfilling is the disposal method used for the majority of U.S. MSW and the ultimate destination for a large fraction of compostable materials. Many consumers perceive compostable and biodegradable plastics in the landfill as preferable to conventional plastics in landfill and their motivation for buying compostable plastics is often not tied to the ability to compost them (Meeks, Hottle, Bilec, & Landis, 2015). Landfill tipping fees in the Southeastern United States are generally low – with an average fee of $46.26 per ton. For comparison, the Pacific and Northeast have average fees of $72.03 and $68.69 per ton, respectively (The Environmental Research & Education Foundation, 2020). In 2018 over 146 million tons of MSW were landfilled nationwide, and food waste was the largest material component landfilled at 24%, followed by plastics at 12% (U.S. EPA, 2020). Landfills also often manage non-MSW materials including C&D waste and industrial byproducts. Food waste and yard trimmings along with paper and other organic wastes generate large amounts of methane in landfill – in 2018, landfills accounted for 15.1% of methane emissions for the United States ("Basic Information about Landfill Gas,"). A number of landfills have implemented projects to convert landfill gas (LFG) into energy – a total of 550 such projects are operational in the U.S. (U.S. EPA). The majority of these projects generate electricity directly.

5.2 Composting

Few facilities in southeast accept food waste and even fewer accept compostable packaging. In Georgia, Athens stands out as one of the few composters that accepts post-consumer food waste and compostable packaging from residents. Other facilities that accept one or both of these feedstocks often only work with a small number of commercial generators.

5.3 Littering and Mismanagement

Plastic packaging materials are often littered, and it is expected that material substitution alone will not meaningfully reduce this phenomenon. There has also been speculation over whether consumer understanding and perception of biodegradation might lead to an increase in littering of these items (UNEP, 2015). Film plastics often escape management operations regardless of polymer type. Several composters surveyed mentioned that biobags and other light plastic films can fly away from piles.

Compostable packaging types like those primarily using PHA are expected to readily degrade in environments beyond managed industrial composting, while PLA-based packaging is more resistant to degradation in the open environment. Effects of potential littering should be considered for a holistic perspective on EOL.

5.4 Athens, GA management system detail

Athens-Clarke County (ACC) landfill has been operational since the 1970s and sits on over 400 acres. Waste is accepted from both Clarke and Oglethorpe counties. Municipal waste collection operated by ACC follows former city boundaries for Athens (**Fig 18**). ACC's collections fleet has both front-loader and rear-loader trucks. The landfill is lined with a plastic geomembrane and methane and groundwater monitoring stations and wells are present in both closed and active cells. Landfill gas collection for the purpose of generating electricity began in 2013 at Athens Clarke County (ACC) Landfill – prior to 2013 this gas was passively vented (**Fig 17**). Leachate is recirculated through a spray system. The EPA estimates a decay rate of 0.057 for ACC Landfill to reflect wet conditions (*EPA Facility Level GHG Emissions Tool - Athens Clarke County Landfill*, 2019).

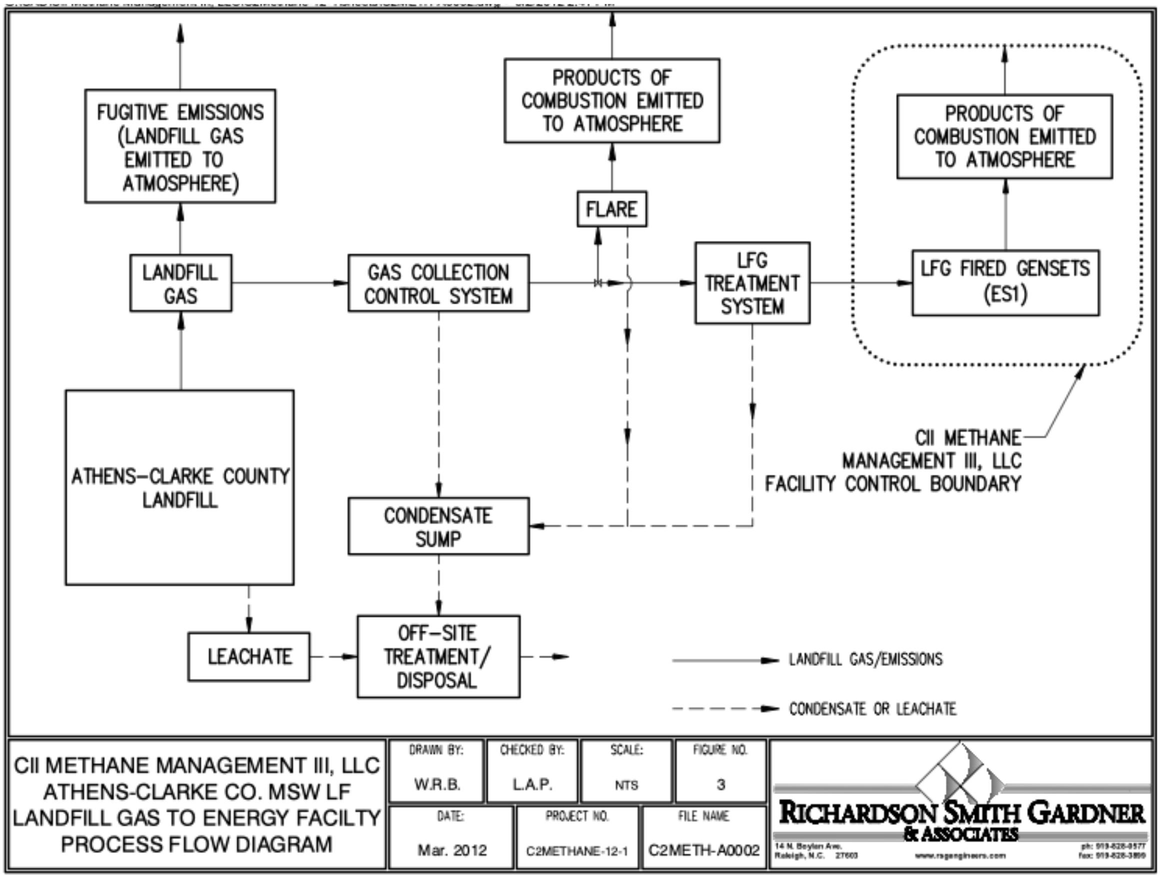

Figure 17: ACC LFG Process Flow Diagram

The ACC composting facility is co-located with the landfill, a common practice for municipalities who manage municipal organics through composting. Co-locating the composting operation with the landfill reduces additional logistics and operations costs and minimizes concerns about odor and other potential nuisances to residents. The composting operation at the landfill opened in 2012. Athens-Clarke County is unique in Georgia as one of the few large-scale composting operations that accepts post-consumer food waste - and the facility accepts waste from a number of generators not restricted to the county. Local commercial establishments such as restaurants and retailers can have their organic waste hauled by the county alongside other collections, although volumes from this sector were far below expectations for 2020 due to disturbances caused by the COVID-19 pandemic. Haulers from areas of metro Atlanta also bring waste to the facility in large loads. Residents of the area can sign up for community curbside pickup subscription services offered by local businesses, or drop off at a number of locations (**Fig. 18**). Carts at these drop off locations are emptied into a modified pickup roll-off trailer (**Fig. 19**).

Incoming organic waste takes an average of 5 months to leave the compost site as finished product, but this timing can vary if incoming material volumes fluctuate widely. Yard trimmings from municipal collections, landscapers and self-haul drop off customers provide the major carbon source and some of this material is chipped before forming piles. These piles are loaded on top of pipes equipped with blowers – this method is called Aerated Static Pile (ASP) (**Fig. 20**). Temperature of piles is continuously monitored, and piles must remain at thermophilic temperatures for a minimum of 5 days by state mandate. In reality, most piles remain at thermophilic temperatures for 2-3 weeks. After this, piles are moved a few more times and are left to cure for a couple of months. Food waste piles are kept separate from piles containing biosolids, which come from wastewater treatment facilities. This allows separate monitoring for pathogens mandated for biosolids composting, and allows compost customers to choose compost sources, as some customers prefer not to buy biosolids compost.

If incoming loads are visibly contaminated, landfill staff may work with haulers to pick through with rakes to remove plastic, metal and glass. In rare cases loads may be turned away due to excessive contamination; however, county goals around increasing landfill diversion usually make this option unattractive. Contamination is most common with post-consumer residential or event haulers. Unlike the county's recycling program, which operates at a loss, the composting program is mostly self-sufficient. Staffing needs are minimal at the present size and finished compost is sold for $20-$25 a ton. Contamination costs the facility in terms of time invested in picking. In addition, if visible contamination is present in finished compost, it can negatively affect demand (although this is rare for ACC and the few cases of complaint have been related to glass).

Material that does not break down in compost piles such as large branches is used at the landfill as intermediate cover to help grow grass. However, if contaminants are found at the end screening stage, they may be landfilled.

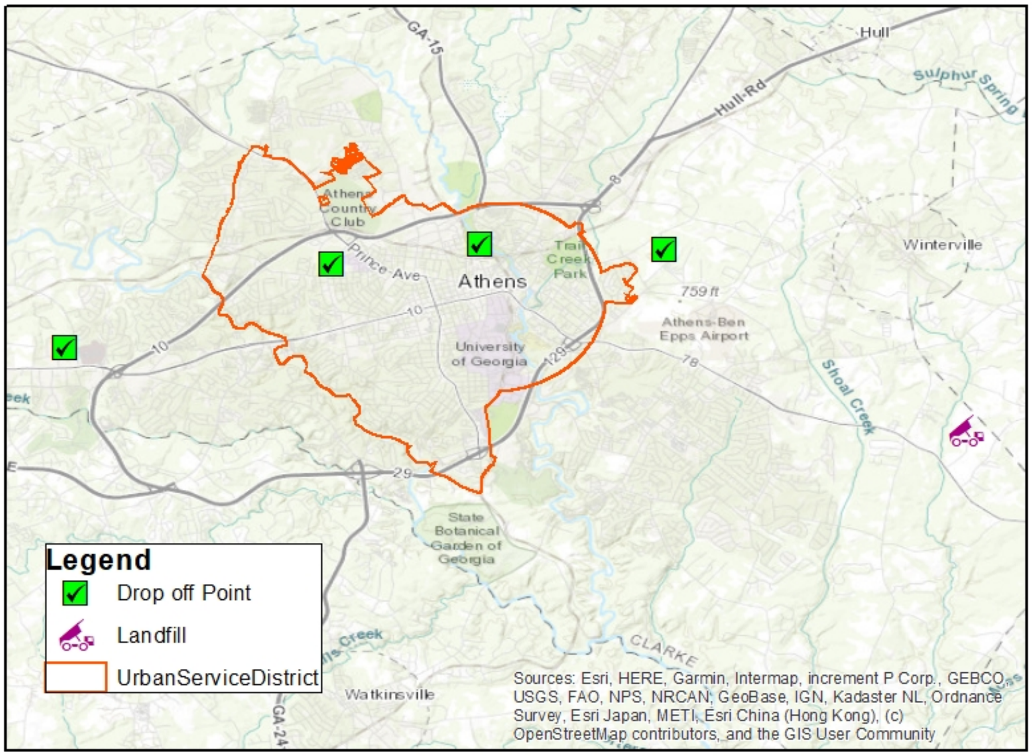

Figure 18: Athens Area map
Compost Drop off sites, municipal collections area and landfill

Figure 19: ACC Compost Collections

Figure 20: ASP system at ACC Compost

CHAPTER 6. MATERIALS AND METHODS

6.1 Goal and Scope

The aim of this study is to assess and compare the impacts caused by end-of-life treatment and management for compostable bioplastic packaging after it has been used and discarded. The study is focused on the context of greater Athens, GA. The findings of this study can be used to inform decision makers and stakeholders in implementation and management of compostable plastic packaging.

The functional unit of the study is the waste management of 1 kg of a number of compostable packaging types that are increasingly used as substitutions for conventional plastic packaging, introduced in **Section 2.2** and detailed further in **Section 6.2.1**.

System boundaries (**Fig. 21**) begin at collection of waste and include disposal at landfill as well as alternative management through composting. Included in the scope is transport from consumer to any processing locations and to final disposal, as well as the operation of processing facilities and equipment. As the focus is on packaging after it has already become waste, the bioplastic itself is considered to carry no burden from upstream production and use. Any co-products will be accounted for through system expansion with substitution.

Also included in this study is consideration of littered or mismanaged compostable packaging waste, also indicated in **Fig. 21**.

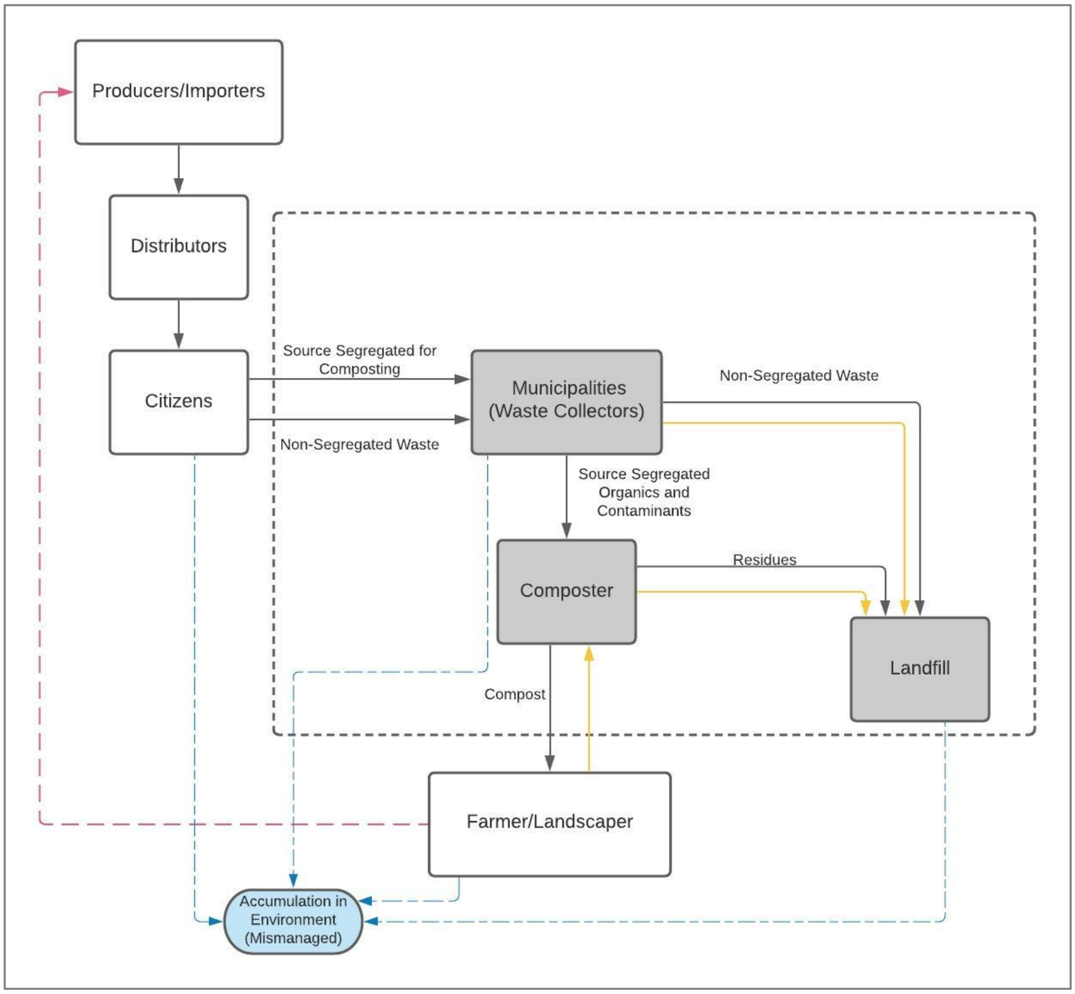

Figure 21: Bioplastic waste system diagram
A black dashed line surrounds the system boundary for this study. Black arrows indicate a mass transfer and yellow arrows indicate a money transfer in the form of tipping fee or compost purchase. Blue arrows represent possible pathways to environmental accumulation.

6.2 General Assumptions and Scenario Limitations

This study takes a mass-based approach to increase simplicity and comparability of modeling assumptions about biodegradable plastic waste; however, this approach does not fully consider functional differences before these materials become waste (during use phase). There is limited consideration given to characteristics that may affect their functional packaging performance. In addition, presence of additives and dyes is largely not considered due to data limitations. However, where possible, degradation data specific to selected applications has been used and is detailed further in following sections.

6.2.1 Scenarios

Scenarios are primarily defined by the choice of packaging examined (**Fig. 22**) and whether this packaging waste is source separated with other compostable wastes or comingled with all municipal waste (**Fig. 23**). Scenario 4 for low density polyethylene (LDPE) is included for comparison with non-biodegradable plastic considered in the same assessment framework (**Table 7**). Packaging materials chosen reflect: 1) attention from industry and regulators as alternatives for single-use plastic products being targeted for substitution; 2) data availability from literature on physical characteristics and degradation behavior; and 3) illustrative examples of the diversity of behavior of different types of biodegradable plastics in waste management systems.

Table 7: Scenarios

Functional Unit	Scenario	Disposal
1 kg PLA clamshells	***PLA-C***	Composting
	PLA-L	Landfill
	PLA-M	Littered / Mismanaged
1 kg MaterBi bag	***MTB-C***	Composting
	MTB-L	Landfill
	MTB-M	Littered / Mismanaged
1 kg PHA straws	***PHA-C***	Composting
	PHA-L	Landfill
	PHA-M	Littered / Mismanaged
1 kg LDPE film	***LDPE-C***	Composting
	LDPE-L	Landfill
	LDPE-M	Littered / Mismanaged

Figure 22: Material Wastes for Scenarios
a) PLA clamshell; b) MaterBi bag; c) PHA straw; d) LDPE film

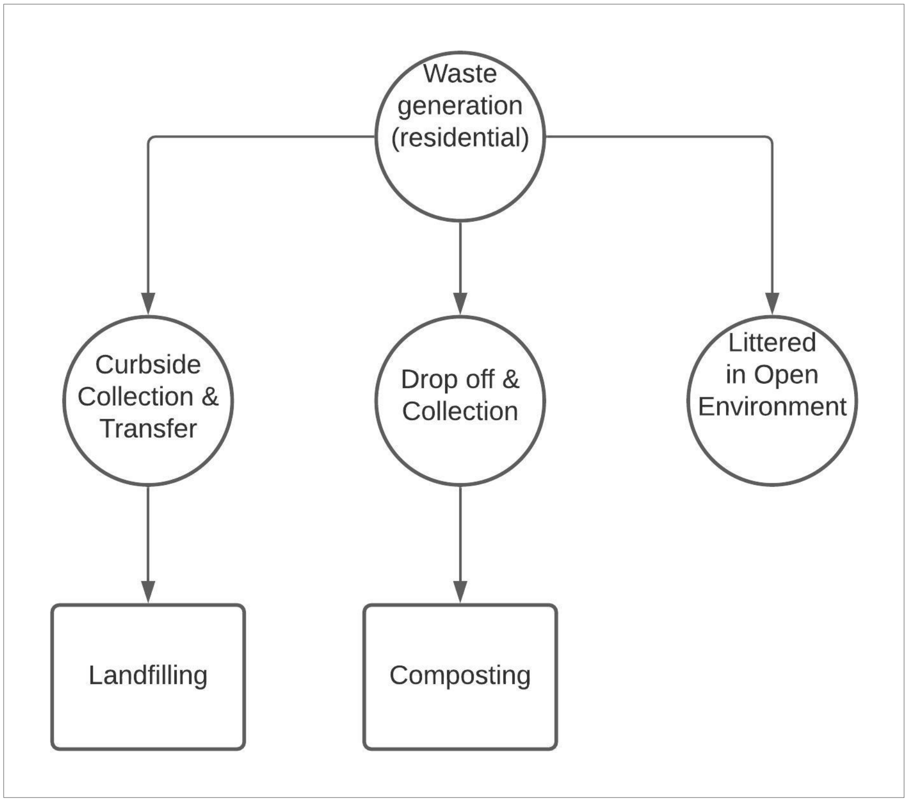

Figure 23: Scenarios

6.2.2 Modeling Tools

EASETECH provides detailed modules for waste management technologies. These modules were modified to reflect conditions of ACC where possible. Customization of these modules will be detailed further in **Section 6.3.**

6.3 Life Cycle Inventory

Key characteristics of the chosen materials in terms of weight, water content, total solids (TS), volatile solids (VS) and chemical composition are used in modeling of composting, landfilling and degradation in the open environment aided by the modeling capabilities of EASETECH (**Table 8**). EASETECH also allows for differentiation of carbon content of biogenic and fossil origin.

An important differentiation for calculation of emissions in all model processes is LCI resulting from *external process contributions*, *process-specific emissions* and *input-specific* *emissions*. External process emissions originate from the use of a material or energy production process. Process-specific emissions are assigned based upon weight of all waste input into said process; input-specific emissions are dependent upon some characteristic of material fractions entering the process. The LCI of a material process is the sum of all of these (**Eq. 1**)(Clavreul, Baumeister, Christensen, & Damgaard, 2014). The basis for each module is detailed in the following sections before discussion of how material inputs were derived for each bioplastic product scenario.

$$LCI_{Material\ process} = \sum_{k=external\ process} LCI_k + LCI_{process-specific} + LCI_{input-specific} \qquad \textbf{Eq. 1}$$

Table 8: Composition characteristics of selected material wastes

Material	PLA	MaterBi	PHA	LDPE
Total wet weight	1 kg	1 kg	1 kg	1 kg
TS	0.996 kg	0.985 kg	0.999 kg	0.999 kg
Water	0.004 kg	0.015 kg	0.001 kg	0.001 kg
VS	0.996 kg	0.945 kg	0.999 kg	0.998 kg
C bio	0.515 kg	0.1519 kg*	0.5834 kg	0
C fossil	0	0.3545 kg*	0	0.848 kg
Source(s)	(Greene, 2018; Kolstad, Vink, De Wilde, & Debeer, 2012; Krause & Townsend, 2016)	(Vasmara & Marchetti, 2016)	(Wang et al., 2018)	(W. Zhang, Heaven, & Banks, 2018)

*0.5064 kg of C was obtained from (Vasmara & Marchetti, 2016). MaterBi composition varies depending upon its formulation; however, data on percentage of starch & PBAT was obtained from (Ruggero, Carretti, Gori, Lotti, & Lubello, 2020) based upon film applications. The C was divided as follows: 30% = 0.1519 kg C bio (starch) and 70% = 0.3545 kg C fossil (PBAT)

6.3.1 Composting - Module overview

Scenarios ***PLA-C, MTB-C, PHA-C, LDPE-C***

Transportation and Waste Collection

It was assumed that organic waste is driven 10 miles by car with 50% of the trip allocated to this activity. After drop off, a distance of 10 miles by municipal collections vehicles is assumed based upon the distance of these points from landfill (**Fig. 18**). The capacity of each collection vehicle is assumed to be approximately 5 tons (see Appendix A-1).

Composting

The composting module first defines degradation of each material as a percentage of material content. Air emissions are assigned based upon these degraded fractions. Solids that are not degraded can then be assigned to the compost or to another output (e.g landfilling of screening residues), and water content can be adjusted accordingly (**Fig. 24**).

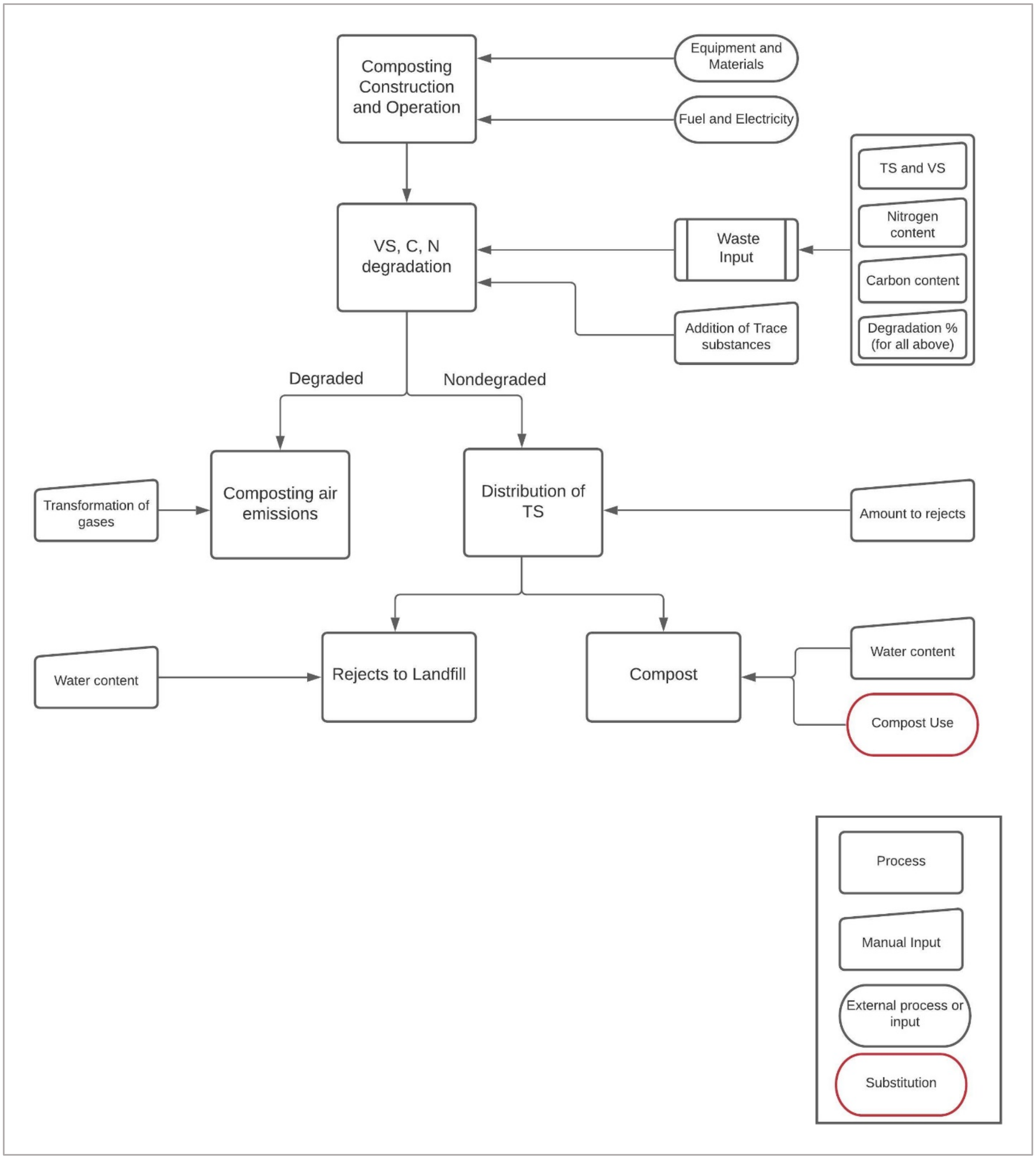

Figure 24: Compost model processes

The modeled processes for composting are summarized in **Table 9**. Detailed processes can be found in the appendix where indicated.

Table 9: Compost model processes

Name of process	Parameter detail	LCI type	Source
Construction and Operation	Piping, Diesel use for equipment; water use	External process	Consultation with ACC**
VS, C, N Degradation	C Degradation	Input specific	See section 6.3.2
	VS Degradation	Input specific	
Composting air emissions	Transformation of gases	Process specific	EASETECH*
Distribution of TS	Amount to rejects	Input specific	See section 6.3.2
Compost	Compost use substitution	Process specific	EASETECH**

*99.8% of degraded carbon goes to carbon dioxide; 0.02% is degraded into methane but 95% of this portion is then oxidized to carbon dioxide as well
**See Appendix A-2

6.3.2 Composting – bioplastic material scenarios

Past bioplastic LCAs have assumed a 60% or 80% conversion of carbon content into air emissions with the remaining 40/20% of carbon remaining in finished compost regardless of differences in degradation behavior between materials (Hottle et al., 2017; Rossi et al., 2015). However, the materials considered here have enough difference in degradation behavior in simulated and field compost environments that a unique degradation rate is defined for each (**Table 10**).

While methodology for measuring biodegradation of materials in lab-scale experiments is generally standardized (if only for certification purposes) (**Table 1**), the suitability of these lab-scale experiments as a stand-in for performance of materials in real-world field conditions at composting facilities is not agreed upon. Lab testing of materials is often done on powder or thin sheet films, which is also not always representative of end product types – increased thickness of products is found to generally hinder degradation speed (Castro-Aguirre, Auras, Selke, Rubino, & Marsh, 2017). In addition, the method of composting (ASP vs windrows or in vessel) has also been found to affect degradation rates of compostable products (H. Zhang et al., 2017). While lab-scale testing involves extended periods of thermophilic conditions, compost piles are generally kept at thermophilic temperatures for a period far below 90 or 180 days.

Following the thermophilic phase, during the curing period temperature may remain elevated at mesophilic temperatures before returning to ambient temperature. ACC standard practice involves thermophilic temperatures for a period of around 14-20 days, after which piles cure. Studies chosen for degradation data reflect testing conditions similar to these operating procedures or were adapted to reflect real-world practice.

For ease of data selection and consistency, it was assumed for all selected materials that the amount of carbon degraded was equal to the amount of volatile solids degraded. The percentage of remaining solids sent to rejects was derived from consultation with ACC and reasonable assumptions around amount of discernible product left in piles going through screening (e.g. it was assumed that some undegraded rigid plastic would be removed while most film would not due to difficulty of screening).

Table 10: Composting Degradation

<table>
<tr><th>Material</th><th colspan="2">Degradation of C (%)</th><th>VS to rejects (%)</th><th>Source(s)</th></tr>
<tr><td>PLA clamshell</td><td colspan="2">75</td><td>10</td><td>(Emadian, Onay, & Demirel, 2017; H. Zhang et al., 2017), consultation with ACC</td></tr>
<tr><td rowspan="2">MaterBi bag</td><td>88 C bio</td><td>18 C fossil</td><td rowspan="2">5</td><td rowspan="2">(Ruggero et al., 2021), consultation with ACC</td></tr>
<tr><td colspan="2">40 overall</td></tr>
<tr><td>PHA straw</td><td colspan="2">95</td><td>0</td><td>(Greene, 2018); consultation with ACC</td></tr>
<tr><td>LDPE wrapper</td><td colspan="2">0</td><td>100</td><td>(Alassali, Moon, Picuno, Meyer, & Kuchta, 2018)</td></tr>
</table>

6.3.3 Landfilling - module overview

Scenarios ***PLA-L, MTB-L, PHA-L, LDPE-L***

Transportation and Waste Collection

It was assumed that mixed municipal waste is collected on an urban route by collections vehicles. The capacity of each collection vehicle is assumed to be approximately 10 tons (see Appendix A-2).

Landfilling

Landfill modules in EASETECH allow customization of landfill gas generation and management as well as leachate generation and management. The processes are summarized in **Fig. 25** with inclusion of relevant inputs that can be customized by users. Landfill construction and operation is included; however, the significance of this process for LCI is limited when considering the entire system of landfill operation (Group, 2011; Levis & Barlaz, 2011). The majority of life cycle impacts resulting from landfill operations and management are attributable to landfill gas and leachate. Of particular importance, especially for greenhouse gas impacts, is the definition of methane potential, carbon content, and decay rate. These are detailed further in the following **Section 6.3.4**.

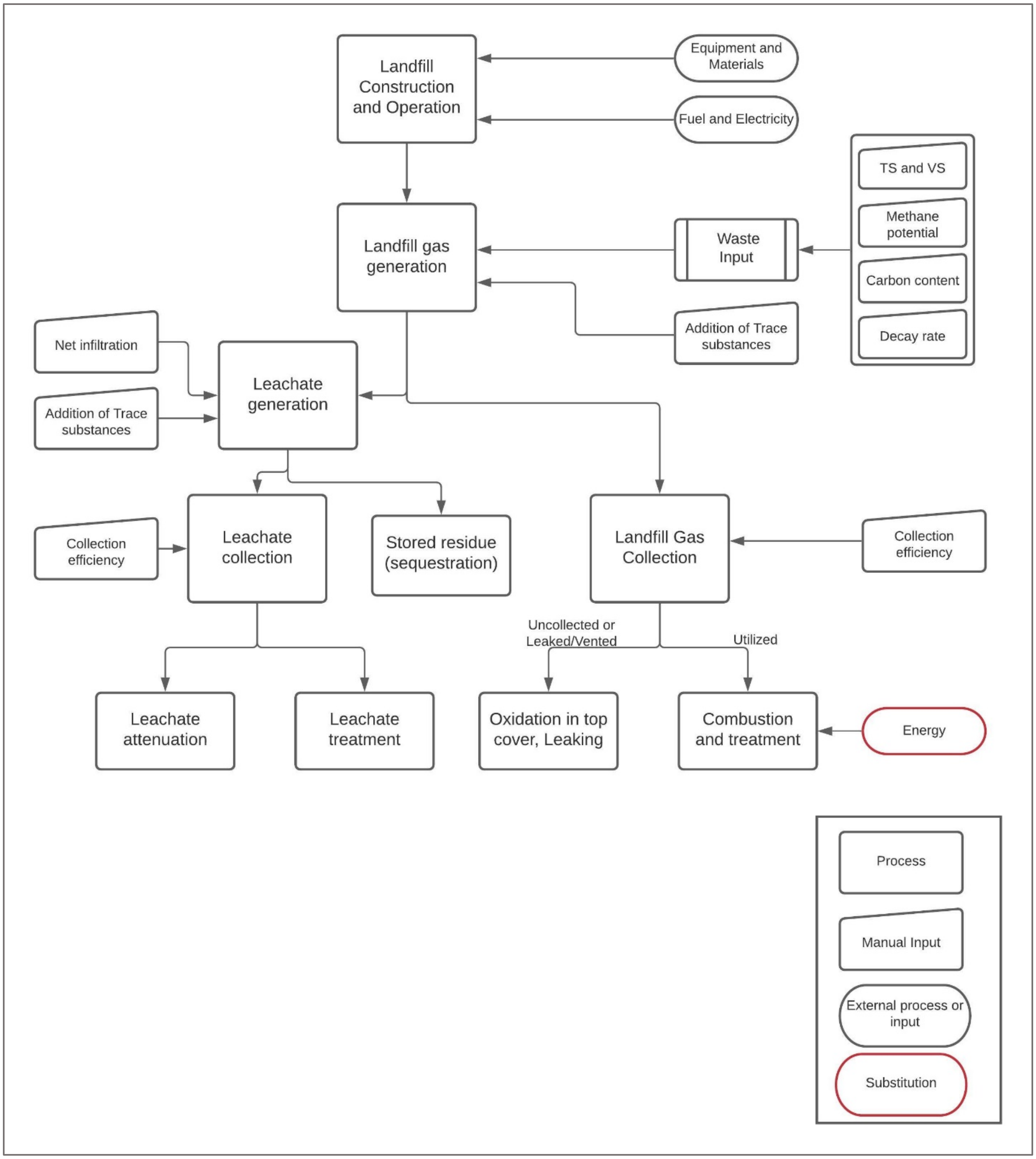

Figure 25: Landfill model processes

The modeled processes for landfilling are summarized in **Table 11**. Detailed processes can be found in the appendix where indicated.

Table 11: Landfill model processes

Name of process	Parameter detail	LCI type	Source
Landfill construction and operation	Consumption (fuel, materials)	External process	EASETECH, with electricity modified to US*
Landfill gas generation	Methane potential	Input-specific	See Section 6.3.4
	Decay rate	Input-specific	
	Addition of trace substances	Process-specific	EASETECH, derived from average of US landfills*
Landfill gas collection	Collection efficiency, Leaking rate of gas	Process-specific	EASETECH, derived from average of US landfills*
Oxidation in top cover	Transformation of materials into emissions	Input-specific	EASETECH*
Combustion and treatment	Transformation of biogas	Input-specific	EASETECH*
	System operation	Process-specific	EASETECH*
	Heat and energy substitution	External process	US grid electricity*
Leachate generation	Infiltration and addition of substances	Process-specific	EASETECH*
Leachate collection	Collection efficiency	Process-specific	EASETECH*
Residue sequestration	Carbon storage	Input-specific	EASETECH*
Leachate treatment	Electricity use	External process	US grid electricity*
	Emissions to air, water, soil	Input-specific	EASETECH*

*full details in Appendix A-3

6.3.4 Landfilling - bioplastic material scenarios

Lab-scale and field-scale testing for anaerobic degradation of biodegradable plastics is far less extensive than the literature surrounding aerobic degradation through composting, marine and soil conditions. Past studies have used a mix of testing methods. Standard methodology for estimation of methane potential of biopolymers and bioplastics (in anaerobic landfill conditions) is largely unresolved in existing LCA and solid waste literature due to uncertainty around appropriate temperature representative of landfill conditions (Krause & Townsend, 2016). In addition, there is limited experimental data on both simulated and field degradation of bioplastics in anaerobic landfill conditions, which can make estimation of decay rate difficult (Levis & Barlaz, 2011). Two sets of data (mesophilic and thermophilic) used for estimation of BMP of selected bioplastic products relevant to landfilling was sourced from existing literature further detailed in the following section.

EASETECH uses a parameter termed "C bio and" to translate the methane potential of a material fraction into kg of Carbon – it designates the part of organic carbon that is anaerobically digestible (**Eq. 2**). "C bio and" for all materials considered is detailed in **Table 12**.

$$C_{bio-and}(kgC/kgTS) = \frac{CH_4pot(m^3/tVS)*VS(\%TS)*\ 10^{-6}(t/g)*12(g/mol)}{CH_4\%(\%\ in\ biogas)*0.0224\ (m^3/mol)} \qquad \textbf{Eq. 2}$$

Landfill gas generation is based on a first order decay (FOD) model. All of the carbon in "C bio and" is ultimately degraded, with the rate following a first order degradation curve (and decay rate k). The remaining carbon will not be degraded and will remain stored in landfill. The mass of "C bio and" in the waste at year T is defined in **Eq. 3**, while the mass decomposed is defined in **Eq. 4**. The carbon is emitted as both methane and carbon dioxide.

$$C_{bio-and_T} = C_{bio-and_{(T-1)}} * e^{-k} \qquad \textbf{Eq. 3}$$

$$C_{degraded_T} = C_{bio-and_{(T-1)}} * (1 - e^{-k}) \qquad \textbf{Eq. 4}$$

A bulk MSW decay rate of 0.04 yr^{-1} is estimated as the average for US landfills (Group, 2011). Decay rate can have significant effects on landfill gas – even though changing the decay rate (to a non-zero value) will not change the ultimate amount of carbon degraded, the efficiency of landfill gas collection is defined by length of time in landfill and high decay rates can lead to larger proportions of gas escaping capture (Levis & Barlaz, 2011). In addition, the LCIA used in this study only considers carbon emitted on a 100-year time scale, so carbon remaining after this period is treated as storage by this study.

Material-specific decay rates can be estimated by comparing lab-scale degradation of material fractions to that of bulk MSW and applying the proportion to field-scale observations (Cruz & Barlaz, 2010). However, a representative waste composition in lab testing is necessary for estimation of a field decay rate. Testing of amorphous PLA for determination of methane potential and decay rate in the past used blank inoculum as a model fitting parameter in place of MSW, but does not apply to the selected crystalline application (Kolstad et al., 2012). Given the range of data sources used for BMP values, decay rates were estimated based upon known decay rates of materials with similar carbon content and degradation behavior and were kept consistent for all considered materials (**Table 12**). Further discussion of decay rates and their influence upon results can be found in **Section 7.2**

Table 12: Anaerobic LFG potential calculation & sources

Material	Methane potential $(\mathrm{m}^3/\mathrm{tVS})$	Source(s)	Methane ratio in biogas	Source(s)	C bio and	Decay rate (per year)
Mesophilic						
PLA clamshell	0	(Kolstad et al., 2012; Krause & Townsend, 2016; Vasmara & Marchetti, 2016)	N/A		0	
MaterBi bag	33	(Vasmara & Marchetti, 2016)	60%	estimate	0.0295	0.02
PHA straw	483.8	(Wang et al., 2018)	65%	(Wang et al., 2018)	0.3987	0.02
LDPE film	0		N/A		0	
Thermophilic						
PLA clamshell	243	(Krause & Townsend, 2016)	60%	(Yagi, Ninomiya, Funabashi, & Kunioka, 2014)	0.2170	0.02
MaterBi bag	108	(Vasmara & Marchetti, 2016)	60%	estimate	0.0964	0.02

PHA straw	367.9	(Hegde, Diaz, Dell, Trabold, & Lewis, 2021)*	65%	(Wang et al., 2018)	0.3032**	0.02
LDPE film	0		N/A		0	

*the value from Wang et al was modified by the factor obtained by Hegde et al for the difference between mesophilic and thermophilic degradation
**this value represents data with high levels of uncertainty due to variance in obtained results when considering ratio of PHA to food waste in digestion

6.3.5 Littering and Mismanagement

Scenarios ***PLA-M, MTB-M, PHA-M, LDPE-M***

It is known that all packaging types considered in this study are often littered and may also be susceptible to leakage in the open environment during waste management (escaping by wind or weather during transport, landfill, or compost), especially films and straws. Data from Marine Debris Tracker has shown that rigid plastic fragments, straws, and film plastic bags are among the most likely to be found in litter assessments and these items are among the most littered in aquatic ecosystem studies globally (**Fig. 26**). However, likelihood of leakage is not considered as a metric for comparison due to lack of reliable data and the focus on mass of waste as functional unit. Instead, possible degradation behavior of materials after littering and mismanagement is used as a basis for comparison and discussion. Data that indicates persistence in some environments is available from testing done to reflect marine and soil environments. Data conducted in field and lab test environments reflecting marine and soil environments was gathered to reflect the diversity of persistence of compostable products and is discussed in **Chapter 7** along with LCIA results.

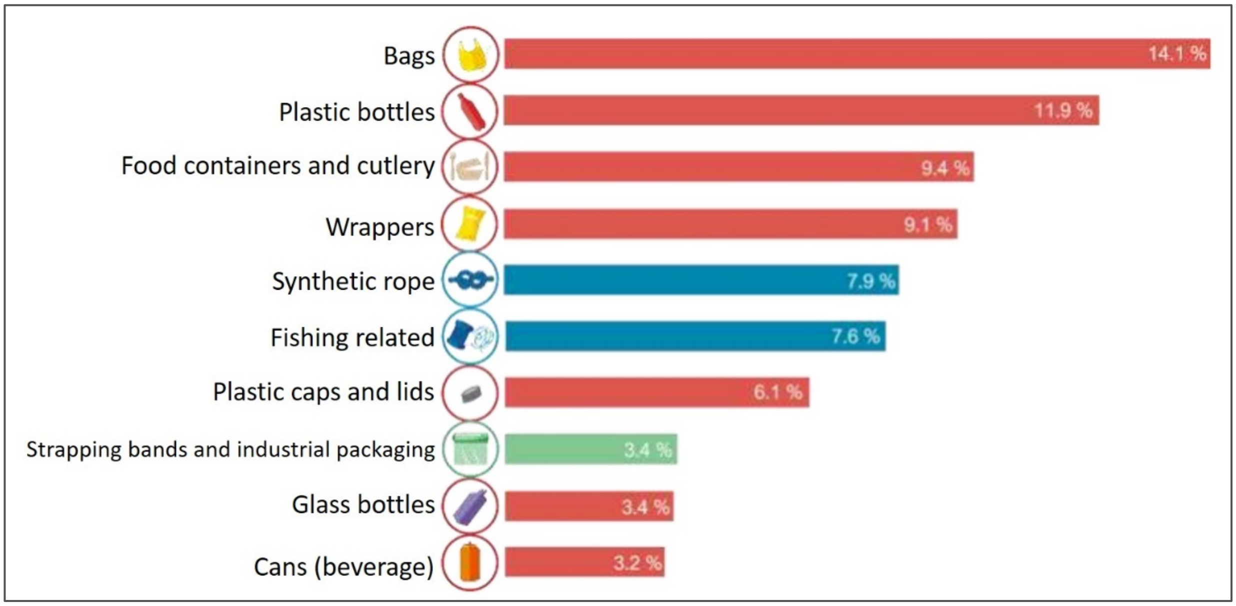

Figure 26: Top 10 litter items across seven aquatic ecosystems globally
(Morales-Caselles et al., 2021)

6.4 Life Cycle Costing Inventory

Internal costs were gathered through input from ACC and past literature on equipment, fuel and site materials used at compost site and at landfill, as well as fees and labor costs, to complement the simultaneous environmental impact assessment. The goal for assessment was to compare how the functional unit of 1 kg of waste affected the costs and revenues of the waste management system, but did not include externality costs. Budget costs were annualized and related to the annual throughput of the relevant facility or usage rate of machinery. Main costs for the Athens-Clarke County compost site are summarized in **Table 13**.

Table 13 – Athens Clarke County compost costs

Operating Fleet and Fuel - Components	Tractor, Screen, Loaders, diesel, tires
Operating Fleet and Fuel - total	$95,557/yr
Structures – components	Pad, tin building, pump station
Structures - total	$21300/yr
Testing and certifications – components	Soil control lab, fed ex, ASI, transport, USCC

Testing and certifications - total	$7226/yr
Equipment – components	Temp meter, O2 meter, pond pump, weather station, nasal ranger
Equipment total	$1660/yr
Tonnage throughput	12500 tons/yr
Compost Sale price	-$20/ton for food waste compost, -$25/ton for biosolids compost

6.5 Environmental Impact Assessment

The ReCiPe LCIA method (Huijbregts, 2016) was used to assess the environmental impacts for different material end-of-life scenarios. A 100 year time horizon was used for calculation of all impacts, including operation of landfill and landfill gas management. The hierarchist perspective was used with ReCiPe 2016 – this perspective balances short term and long term impacts (Huijbregts, 2016). ReCiPe includes 18 midpoint indicators and 5 endpoint indicators, and selected indicator results are highlighted in **Sections 7.1-7.5**.

CHAPTER 7: RESULTS AND DISCUSSION

7.1 ReCiPe Endpoint Indicators and added Persistence Indicator

Fig. 27 shows the final endpoint scores for each scenario normalized to 100 as the highest absolute value for each endpoint as a means of comparison, along with the added indicator for Persistence in the Environment. All composting scenarios have relatively similar scores for all endpoints when compared to other scenarios and materials; however, landfilling scenarios exhibit wide variety, with many endpoint values receiving large credits (reflected here as negative scores), especially PLA and PHA in mesophilic landfill scenarios. This wide variation is largely due to just a few midpoint indicators that factor into multiple endpoints – namely climate change, which has an outsized influence on scores for terrestrial ecosystems, freshwater ecosystems and human health. Climate change midpoint scores are highly sensitive to assumptions around carbon storage and landfill gas management, explored further in **Sections 7.3-7.5**.

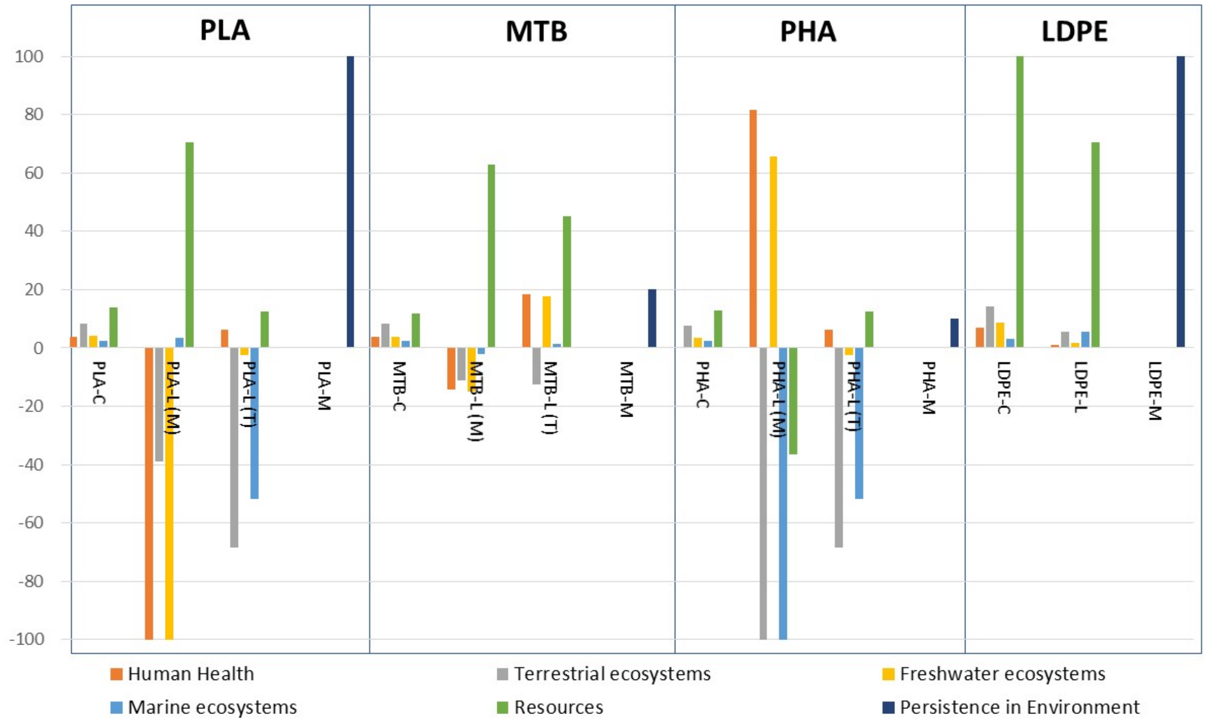

Figure 27: ReCiPe Endpoint Scores and Persistence Indicator for all Scenarios
Scores are normalized to 100 as the highest absolute value for each indicator

Fig. 28 reflects data sourced from lab-scale degradation tests that simulate aerobic marine conditions at similar temperatures and conditions (25-30 C) and percent of material remaining after ~180 days. Although this type of testing does not reflect all conditions realistic to mismanaged and littered waste, it reflects the difference in expected persistence in the environment of the chosen materials considered in this study. PLA clamshells and LDPE film packaging are not expected to meaningfully degrade in the open environment. PHA has been shown to almost completely degrade in this testing environment, and MaterBi bags degraded more than 80% over 180 days. However, biodegradation has been found to be highly sensitive to shape and surface area of samples tested (Wang et al., 2018), and many studies test samples that have been reduced in size. Therefore, while these values function as a way to compare expected degradation, values have high levels of uncertainty when used as a stand-in for expected behavior in real-world conditions for the products chosen.

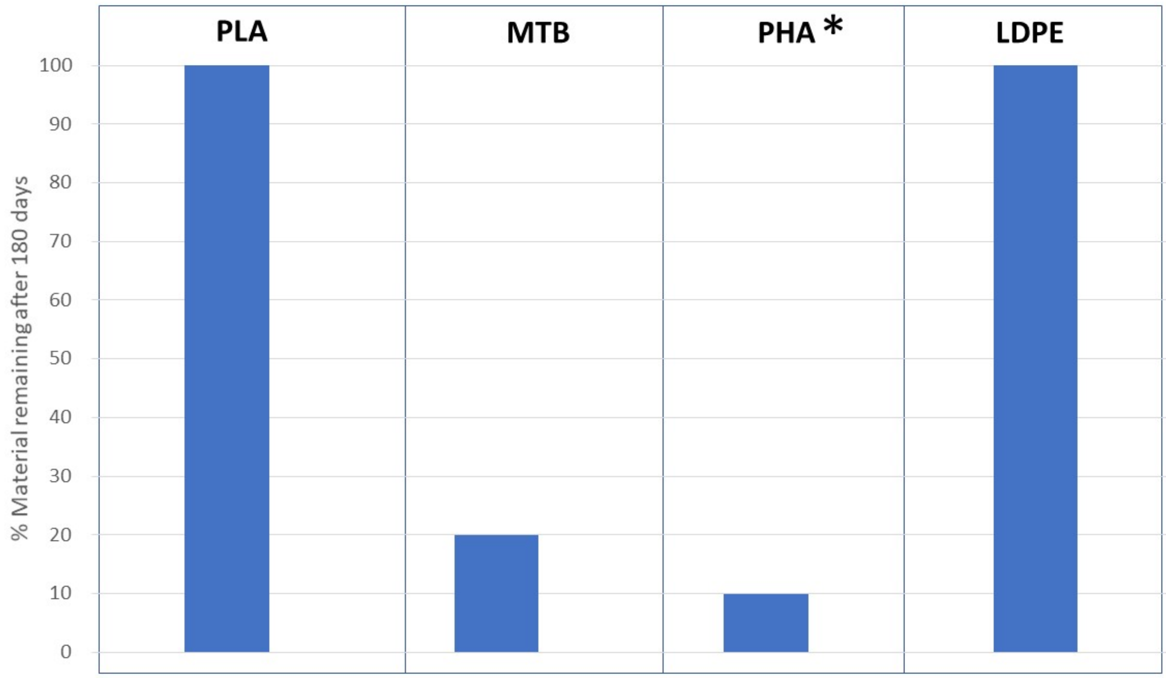

Figure 28: Persistence in Environment Midpoint Indicator
Percent remaining after 180 days in aerobic marine lab-scale testing; PLA:(Greene, 2018); MaterBi (Mater-Bi;, 2018); PHA: (Greene, 2018; Wang et al., 2018)*; LDPE (Civancik-Uslu et al., 2019); *high levels of uncertainty were obtained for PHA samples of different sizes; therefore, a value of 10% remaining was used as a functional “average” of valued obtained in the cited studies and as PHA straws certified as “OK Biodegradable MARINE” must show 90% biodegradation after 180 days in reference to a cellulose control

7.2 Resource Use

Fig. 29 shows the final endpoint score for resource use for each composting and landfilling scenario. The ReCiPe resource use endpoint is calculated using mineral resource scarcity and fossil resource scarcity. Landfilling scenarios result in higher impact scores than composting, with the notable exception of PHA in mesophilic landfill. The negative score for this scenario is the result of credits for landfill gas combusted for energy generation. Climate change midpoint is also sensitive to landfill gas combustion and is explored further in **Section 7.4**.

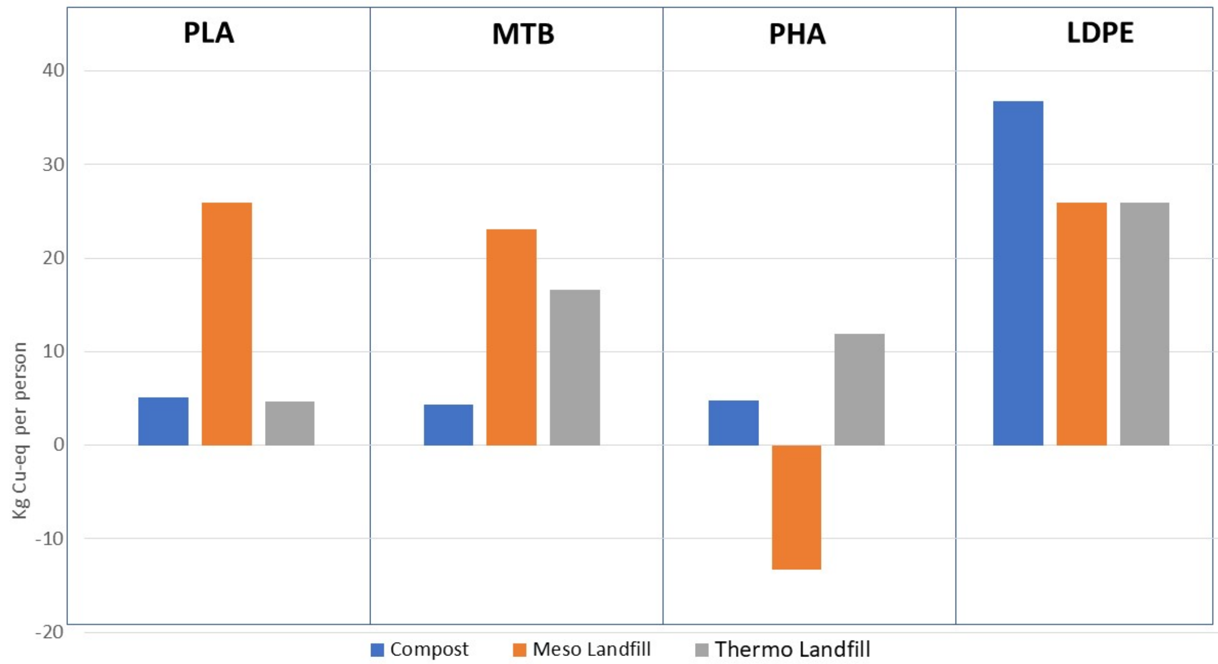

Figure 29: Resource Use Endpoint for Composting and Landfilling

7.3 Climate Change – Landfilling and Composting

Fig. 30 shows the final midpoint indicator score for climate change for each scenario in terms of kg of carbon dioxide equivalent, assessed over a 100 year horizon. For all biodegradable materials, methane potential in mesophilic and thermophilic anaerobic landfill conditions has a large influence on ultimate climate change score.

For PLA clamshells, assumed not to degrade in mesophilic landfill conditions, bio-based PLA material represents a carbon sink with a score of -1.86 kg CO2 eq per kg of PLA clamshells landfilled, while partial degradation in thermophilic landfill conditions leads to a score higher than that of composting (0.118 and 0.0717 kg CO2 eq, respectively). MaterBi bags in mesophilic landfill have a score of -0.263 kg CO2 eq, while composting has a climate change score of 0.0708 and thermophilic landfill leads to a score of 0.340 kg CO2 eq. PHA straws, assumed to be highly degradable in mesophilic landfill conditions, have a climate change score of 1.53 kg CO2 eq; thermophilic landfill conditions lead to a score of 0.655 kg CO2eq and composting produces a climate change score of 0.0583 kg CO2eq. LDPE, inert and fossil-based, has a climate change score of 0.131 kg CO2 eq in composting scenario, but scores of only 0.0190 kg CO2 eq in both mesophilic and thermophilic landfill scenarios.

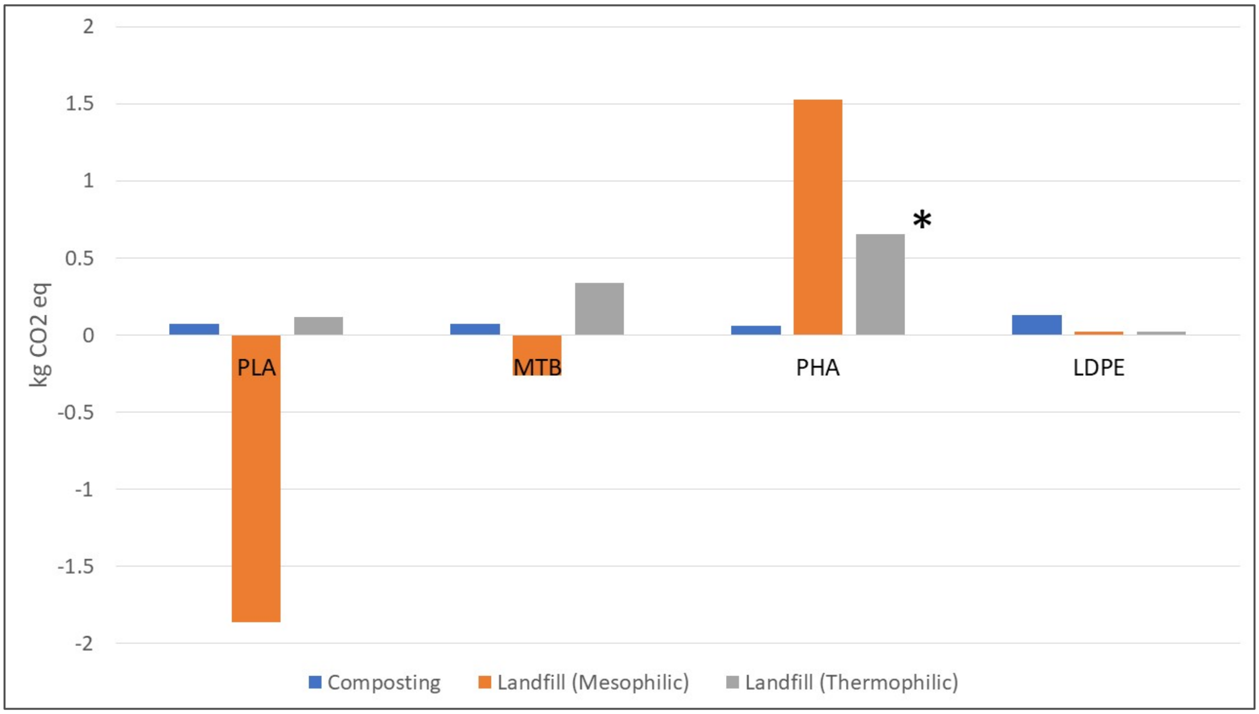

Figure 30: Climate change midpoint for composting and landfilling scenarios
*this value represents data with high levels of uncertainty due to variance in obtained results when considering ratio of PHA to food waste in digestion

The climate change scores obtained fall within the range of 2 previous studies, but the assumptions and methodology used in modeling were slightly different in both. (Rossi et al., 2015) compared landfilling of PLA with industrial composting along with incineration and other waste management options in a European context, and found that PLA in landfill had a negligible global warming impact per kg, while composting led to the equivalent of around 1.8 kg CO2 eq per kg – however, the authors did not consider carbon storage in landfill and treated carbon dioxide degradation from composting as a contributor to global warming potential. (Hottle et al., 2017) found the global warming potential for PLA in low landfill emissions to be almost 0, again not considered carbon storage, and found high landfill emissions to be around

2.5 kg CO_2 eq. In composting they found a global warming potential of around 0.3 kg CO_2 eq per kg. Other materials considered here have not been modeled extensively in end of life scenarios including composting and landfilling.

7.4 Landfilling – Climate change sensitivity

Fig. 31 shows the breakdown per process to the overall climate change score for landfilling scenarios. While PLA and LDPE are both assumed to resist degradation in mesophilic landfill, only PLA represents carbon storage in this model, as biogenic carbon is part of the short-term carbon cycle and fossil-based plastic is not. In addition to carbon sink of undegraded material, thermophilic landfill scenario also credits PLA with a small offset of electricity from landfill gas utilized. MaterBi bags are unique in materials considered in that part of the carbon in this material is of fossil origin. Therefore, while very little degradation is expected in mesophilic landfill conditions, carbon storage is much smaller than the value for PLA.

Oxidation of landfill gas in landfill cover (uncollected gas) is the largest contributor to climate change scores of the materials with the highest scores. PHA modeled in mesophilic conditions is highly degradable and leads to the highest climate change score of scenarios considered, despite a small credit for combustion of LFG for energy generation. Interestingly, (Hegde et al., 2021), found that PHA was more resistant to degradation in thermophilic conditions and the climate change results reflect this data input into the model.

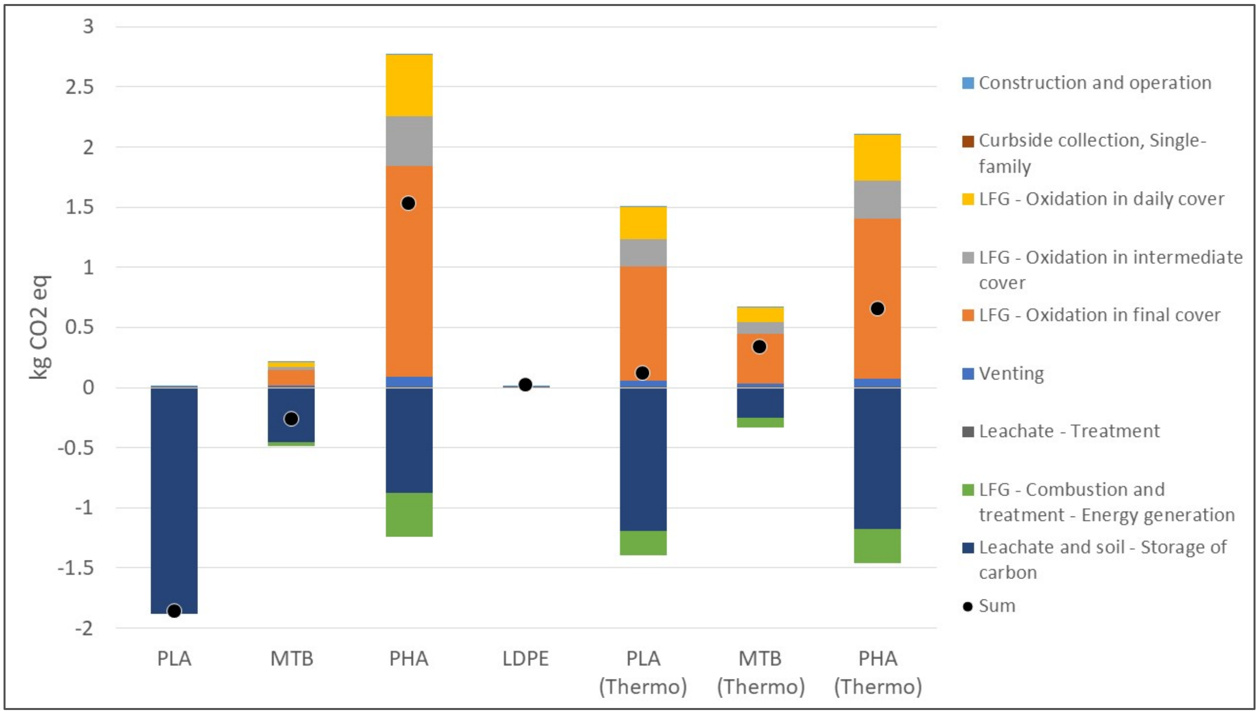

Figure 31: Climate Change midpoint for landfilling scenarios
Black dots mark the overall score (including both emissions and credits)

Fig. 32 and **Fig. 33** illustrate the effect that assumptions around material decay rates and landfill gas management efficiency have on scenario climate change score results. As shown in **Fig 32**, k rate is most consequential for materials with higher levels of degradability (higher anaerobic methane potential). For PHA straws in mesophilic conditions, a k rate of 0.01 per year results in an overall score of 0.742 kg CO2 eq, while k rates of 0.02 and 0.03 per year lead to scores of 1.53 and 1.72 kg CO2 eq, respectively. Higher k rates mean that more material is ultimately degraded over the 100 year timescale considered, and while some landfill gas is captured, this still leads to an increase in oxidation of landfill gas and overall climate change contributions. However, if data obtained from thermophilic degradation testing is used in the model, lower k rates considered result in a minimal score for PHA straws in landfill, as a large proportion of carbon remains stored in landfill.

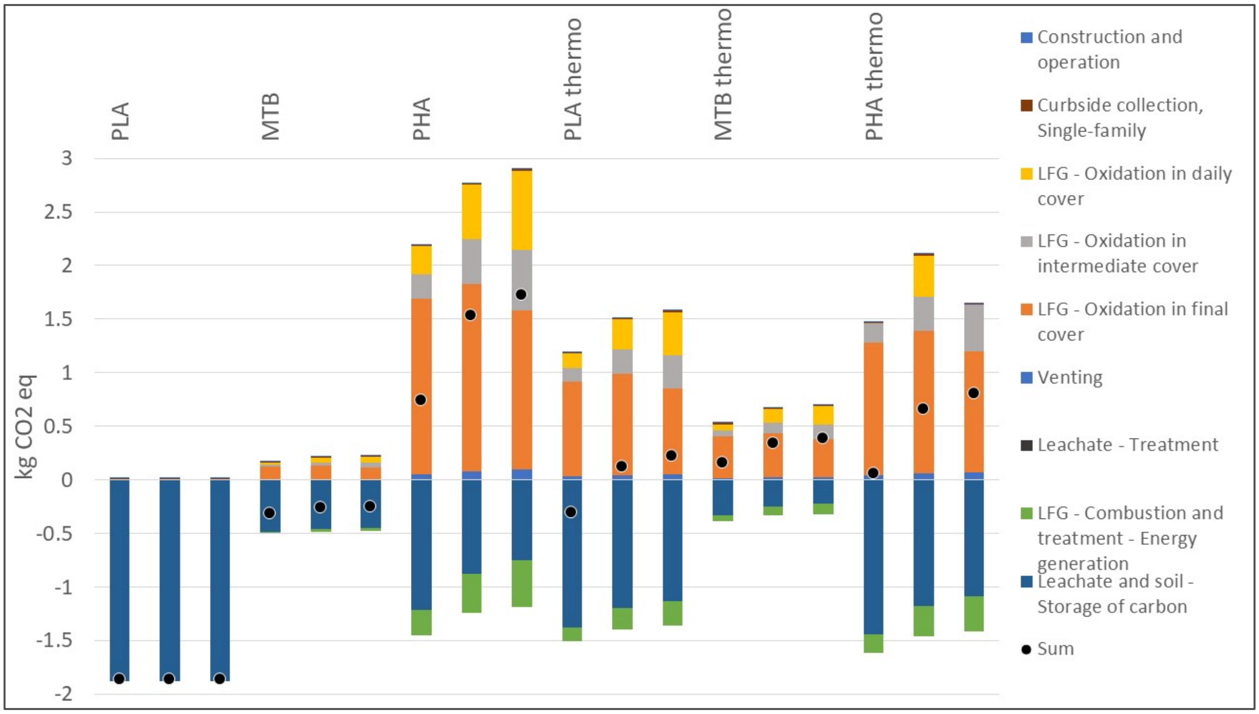

Figure 32: Climate change midpoint for landfilling scenarios with k rates of 0.01 per year, 0.02 per year, and 0.03 per year
Black dots mark the overall score (including both emissions and credits)

Fig. 33 shows the effect that assumptions around landfill gas capture efficiency have on obtained results. Average performing landfills are assumed to collect 35% of LFG generated in the first 5 years, 65% in the next 10 years, 75% in the next 40 years and 0% after 55 years. In contrast, state-of-the-art, high performance landfills are assumed to collect 45% of LFG generated in the first 5 years, 80% in the next 10 years, 95% in the next 40 years and 0% after 55 years. A high-performance landfill gas collection system results in a climate change score of 0.721 kg CO2 eq for PLA in mesophilic landfill, approximately half of the score obtained with less optimistic LFG capture rates.

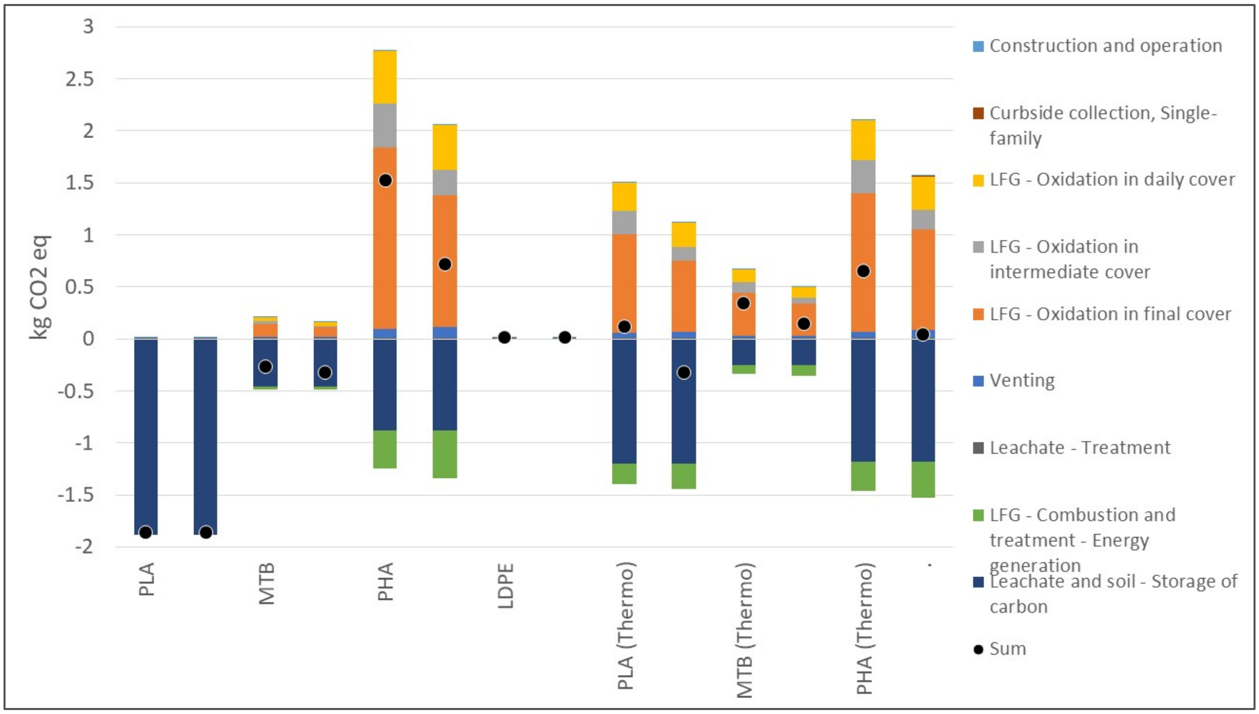

Figure 33: Climate change midpoint for landfilling scenarios with average and high-performance landfill gas collection
Black dots mark the overall score (including both emissions and credits)

7.5 Composting – Climate Change and Freshwater Eutrophication

Fig. 34 shows the breakdown per process to the overall climate change score for composting scenarios. Transportation by car is the largest contributor to climate change impacts for all scenarios except that of LDPE film. The LDPE film composting scenario represents a case where material does not degrade at all, but enters the composting process alongside other source-separated waste and is ultimately removed by screen before heading to landfill. MaterBi bags and PLA clamshells screened out and landfilled following the composting process also contribute significantly to their score. Overall score contributions from transportation far outweigh that of degradation emissions for all scenarios. Modeling assumptions around degradation also mean that MaterBi bags are the only material to receive significant credit for compost use.

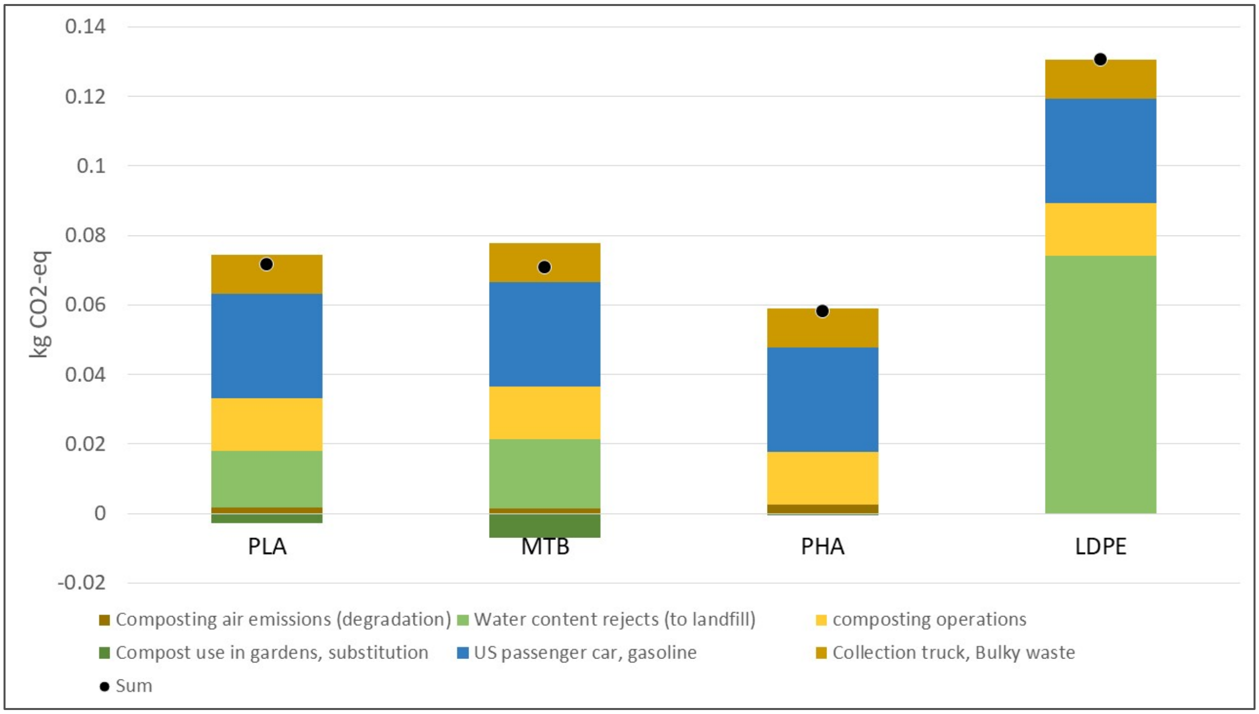

Figure 34: Climate change midpoint for composting scenarios
Black dots mark the overall score (including both emissions and credits)

Fig. 35 also reflects how model assumptions around material remaining in compost affects results for freshwater eutrophication midpoint. Both MaterBi bags and PHA have a negative value for this overall midpoint score due to credits from mass remaining in compost and compost partial substitution for fertilizers.

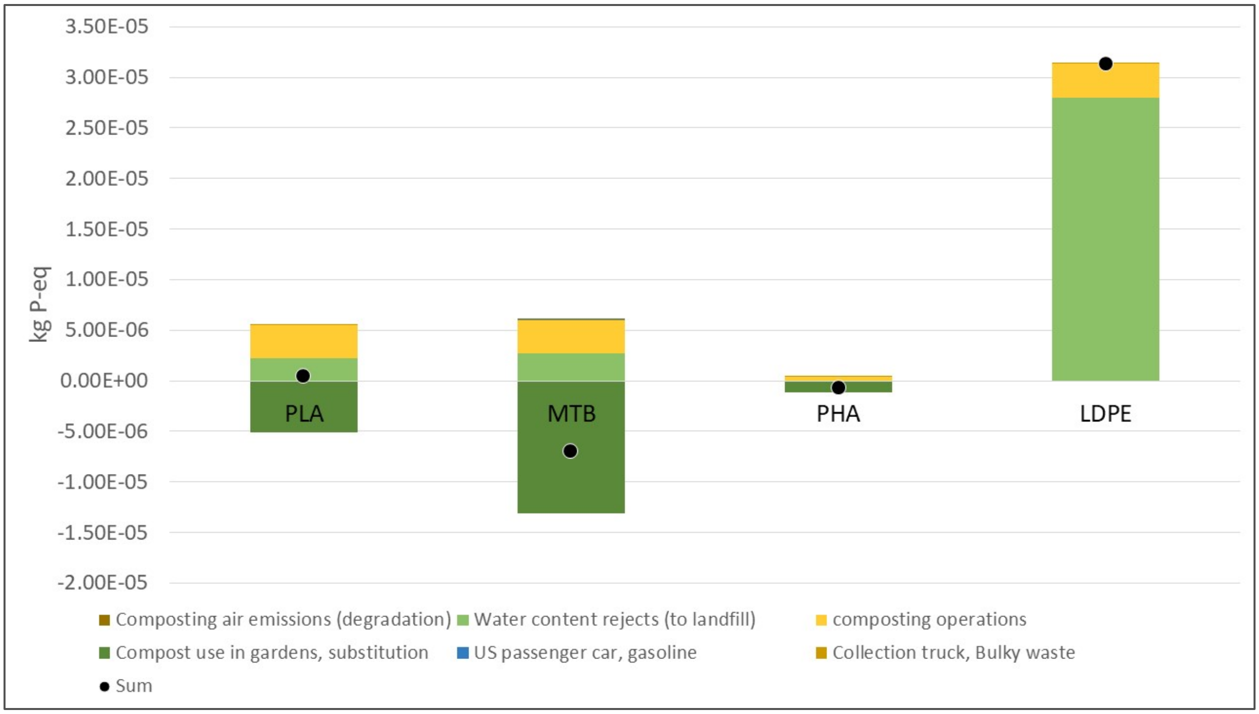

Figure 35 Freshwater eutrophication midpoint for composting scenarios

7.6 Cost for Composting and Landfilling

Normalizing total system cost for ACC compost operations by annual throughput shows that each kg to compost has a cost of approximately 2 cents per kg. This overall value includes costs for the compost pad, air pumping system and heavy machinery. Results for cost of disposal of each type of waste and between landfilling and composting per kg of waste were not meaningfully different. While this study considered effects of differences between screening and contamination in LCIA results, these differences in cost are small unless compounded over time. Landfilling operations are much larger in volume than that of the composting facility at ACC. It is worth noting that ACC composting operations are able to sustain operations based on revenues earned from the same program. This is in contrast to some recycling operations at the county, which operate at a loss.

7.7 Conclusion and Discussion

This study demonstrated the range of possible impacts that compostable packaging materials can have when introduced into waste management systems. Different types of compostable packaging can have different implications for waste management stakeholders. Biodegradable plastic packaging that is designed to readily biodegrade in a variety of environments, such as PHA straws, is likely to contribute to climate change impacts when managed through landfilling, making management through composting a far preferable waste management option. Landfills that are not optimized for capture of landfill gas and reach high temperatures may produce large amounts of methane over time if a significant amount of currently landfilled plastic were substituted with biodegradable plastics. However, composting of this material results in far less climate change impacts, especially if collection and transportation systems are designed to minimize distance.

This study contributes to the literature for Life Cycle Assessment of compostable and biodegradable packaging materials and introduces several components that can be expanded upon in future work. Existing composting infrastructure or lack of composting availability should be considered in future studies, especially in the context of the United States where composters accepting compostable packaging materials are few. In addition, potential contamination from non-biodegradable plastics and differences in degradation rates in composting conditions are considered in this study, in addition to consideration of potential degradation rates in the open environment.

Potential benefit of biodegradable plastics in terms of climate change impacts at end-of-life is maximized if these materials enable diversion of highly degradable food waste and other organics from landfill. Materials that do not fully break down in composting environments, such as inert plastic contaminants and biodegradable plastics that leave plastic fragments in realistic management conditions, may add emissions and costs to waste management systems if entered into composting systems in excess.

In addition, while this study calculated midpoints associated with human health and ecotoxicity (Appendix A-5), results obtained were largely driven by energy use and landfill gas as information available on chemical composition of selected products was limited. Future work should account for additives in biodegradable packaging products, as this is a potential concern especially for mismanaged plastics as several bioplastics have been found to contain toxic chemicals (Zimmermann, Dombrowski, Völker, & Wagner, 2020).

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APPENDICES

A-1 Composter Survey

1.What is the name of your facility? *

_____

2. Where are you located? (Street Address or City, State) *

_____

3. Contact email

_____

4. Contact phone

_____

5. Feedstocks the facility accepts in practice (please select all that apply)*

Regardless of permit specifications, what feedstocks do you accept in practice? Please select all that apply. If Other, please specify.

☐Yard trimmings

☐Vegetative food waste

☐All food waste (including meat, dairy, etc)

☐MRF-processed or unsorted MSW

☐Agricultural wastes

☐Biosolids

☐Septage

☐All certified compostable products*

☐Food-soiled paper

☐Pre-consumer food waste only

☐Pre- and post-consumer food waste

☐Other _____

6. What is the operational structure of the composting facility?

Who owns and/or operates this facility? If Other, please specify (ex. worker-owned cooperative)

☐Private/Commercial

☐Non-profit

☐Public/Municipal

☐Public-Private Partnership

☐Institutional (University, Corporate Campus etc)

☐Other _____

7. What composting method(s) do you use? Are your piles covered?

Please choose all that apply. If Other, please specify.

☐Windrows

☐Aerated Static Pile

☐Static Pile

☐In-vessel or container

☐Other _____

8. (If Covered) How are they covered?

Please select all that apply. If Other, please specify.

☐Structure/Roof

☐Fabric Cover

☐Mulch

☐Finished compost layer

☐Other _____

9. Who can drop off waste at your facility?

Please select all that apply. If Other, please specify.

☐Community / Individual Self-Haul

☐Municipal Government

☐Permitted Haulers

☐We only compost waste from onsite operations

☐Other _____

10. What type of generators does your facility receive feedstocks from?

Please select all that apply, if known. If Other, please specify.

☐Residential

☐Commercial (e.g., restaurants, grocery stores, offices)

☐Industrial (e.g., food production, processing etc)

☐Agricultural Byproducts/Wastes

☐Schools

☐Healthcare facilities (e.g. hospitals)

☐Prisons

☐Municipal wastewater

☐Other ______

11. Does your facility measure incoming materials in tons or cubic yards? **a. If you measure in tons: What is your total tonnage received annually (all feedstocks)?** ☐<5,000 tons per year ☐5,000 - 15,000 tons per year ☐15,000 - 30,000 tons per year ☐30,000 - 50,000 tons per year ☐50,000 - 75,000 tons per year ☐>75,000 tons per year **b. If you measure in cubic yards: What is your total amount received annually in cubic yards (all feedstocks)?** ☐<10,000 cy per year ☐10,000 - 30,000 cy per year ☐30,000 - 60,000 cy per year ☐60,000 - 100,000 cy per year ☐100,000 - 150,000 cy per year ☐>150,000 cy per year **c. If both or other: What is your total amount received annually (all feedstocks)?** Please specify units. ______

12. Are there restrictions on the origin of feedstocks accepted?

Geography: e.g. city only, county only

If yes, please select origin restriction.

☐City/Municipality only

☐County only

☐State only

☐Other _____

13. What is the total amount of food waste received annually?

Measured or estimated OK. Please specify units (e.g. cubic yards or tons, %)

_____

14. What is the total amount of leaf/limb or carbon received annually?

Measured or estimated OK. Please specify units (e.g. cubic yards or tons, %)

_____

15. What soil amendments are produced by your facility? Please select all that apply.

If Other, please specify.

☐Fine-screened compost

☐Half-inch compost

☐Mulch

☐Wood chips

☐Blends (e.g. potting soil, sand, etc.)

☐Alternative Daily Cover (ADC) or other beneficial reuse at landfills

☐Other _____

16. Does your facility measure finished product in cubic yards or tons?

Finished products can include compost, blends, mulch, etc.

a. If you measure in tons: What is the total tonnage of finished compost/finished product made annually?

Total including compost and/or other soil amendments. Estimate OK.

_____

b. If you measure in cubic yards: What is the total amo unt of finished compost/finished product made annually in cubic yards? Total including compost and/or other soil amendments. Estimate OK.

_____

c. If both or other: What is the total amount of finished compost/finished product made annually?

Total including compost and/or other soil amendments. Please specify units. Estimate OK.

_____

17. Does your facility produce certified organic compost?

☐ We only sell certified organic compost

☐ We sell both organic and non-organic

☐ We do not sell certified organic compost

Name of certifier (e.g. OMRI, CDFA, etc): _____

18. Does your facility have STA Certified compost?

☐ Yes

☐ No

19. What is the average price of your finished soil amendment products sold?

Please provide the average obtained by the total of all products sold. Please specify units. Estimation is OK. (E.g. $/cubic yard or truckload)

_____

20. Does this facility have de-packaging equipment?

If so, what can the depackaging equipment handle?

☐Plastic

☐Paper and Cardboard

☐Glass

☐Metal

☐Wood

☐Other _____

21. Please select the processing equipment at your facility.

Select all that apply. If Other, please specify.

☐Sort lines

☐Screens

☐Shredder

☐Grinders

☐Turners

☐Baggers

☐Electric blower

☐Other _____

22. What is the average range for your C:N ratio?

Measured or estimated OK.

_____

23.What is the average temperature of active/thermophilic piles?

______

24. On average, how long does it take for incoming material to leave as finished product?

______

25. How many days is compost active?

On average

______

26. How many days does compost cure?

On average

______

27. Does the ambient air temperature during the winter months affect your composting time/rate?

☐Yes

☐No

28. What are your general observations of packaging/foodservice ware marketed as compostable?

Please provide a short answer.

______

29. Do you have an in-house standard or test for compostable packaging at your facility?

If so, what specifications does packaging need to meet? What tests do you perform or what attributes do you look for?

______

30. Are certifications of compostable packaging important to your facility? (e.g. BPI)

______

31. How are new compostable materials addressed?

For example, new types of compostable flexible packaging.

______

32. What is the permitted acreage at your compost facility?

If not known, estimate OK. If using other unit please specify.

_____

33. What is the approximate square footage of each of the following?

Please note if using units other than square feet. Estimation OK.

a. Active Compost Pad: _____

b. Curing Pad: _____

c. Feedstock receiving and mixing: _____

d. Screening and/or processing: _____

e. Other: _____

34. How many people are employed by your facility?

☐1-5

☐5-10

☐10-20

☐20-30

☐30+

35. Do you face any barriers for expansion? Please select all that apply.

What limiting factors prevent you from accepting more feedstocks and/or increasing throughput? If Other, please specify. If none apply, disregard.

☐Space (no available land, cost of land etc)

☐Permitting/Regulatory (facility type restrictions, environmental requirements, financial burden to comply, etc)

☐Feedstock availability/sourcing (hard to acquire, face competition from other composters or from AD, landfill, etc)

☐Market for Products (limited markets, distance to markets, contamination concerns, etc)

☐Other ______

36. Does your facility benefit from monetary or tax incentives from your state/county/city that were put in place to encourage composting and/or landfill diversion?

If so, please provide brief detail on incentives offered.

______

37. What type of policy has been enacted in your jurisdiction?

Please select all that apply, to your knowledge.

☐No leaf/limb in landfill

☐Commercial food waste / organics - landfill ban or mandatory recycling

☐Residential food waste / organics - landfill ban or mandatory recycling

☐Single-use plastic bag ban

☐Styrofoam/Polystyrene ban

☐Plastic straw bans

☐Other single-use plastic bans

☐Other (please specify)

38. What is your state permit type?

If you are permitted by your state environmental agency, please indicate the category that most closely fits your permit type. If Other, please specify.

☐Solid Waste Facility

☐SSO Composting allowing food waste

☐ Permit by rule or registration

☐ Biosolids composting permit

☐ On-farm composting exemption from permit

☐ Other _____

39. Feedstocks the facility is allowed to accept under permit type (please select all that apply)

Under the type of permit that your facility holds, what feedstocks are you permitted to accept? If there are no restrictions, please select all options. If Other, please specify.

☐ Yard trimmings

☐ Vegetative food waste

☐ All food waste (including meat, dairy, etc)

☐ MRF-processed or unsorted MSW

☐ Agricultural wastes

☐ Biosolids

☐ Septage

☐ All certified compostable products

☐ Food-soiled paper

☐ Pre-consumer food waste only

☐ Pre- and post-consumer food waste

☐ Other _____

40. Which of the following compostable materials are you familiar with?

Please select all that apply.

☐ PLA

☐PBAT

☐PBS

☐Thermoplastic starch (TPS)

☐Starch

☐Cellulose/ Lignocellulose

☐viscose/ cellophane / Nature flex

☐Bamboo/ Bagasse

☐PHA

☐Other _____

Other Notes:_____

A-2 Composting scenarios data for LCI

Distances from compost drop-off points to ACC landfill: 13.5 miles (Bishop), 16.6 miles (Cleveland), 9.4 miles (CHaRM), 7.5 miles (Hancock).

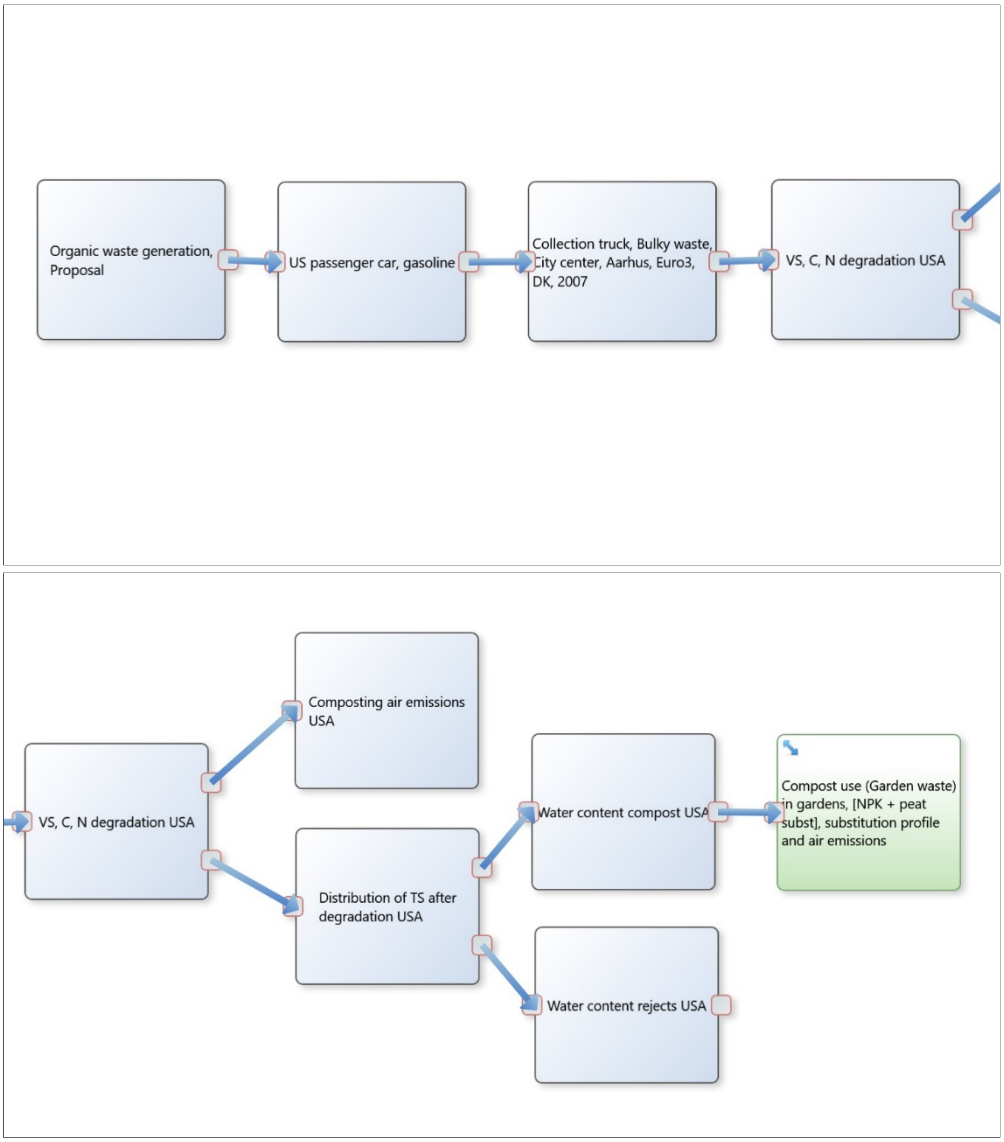

Figure 36 EASETECH model structure - Composting

Table 14. Compost LCI data detail

Scenarios	Process	Name	Amount and notes	Database
PLA-C, MTB-C, PHA-C, LDPE-C (same for all)	US passenger car, gasoline	Transport, passenger car, gasoline powered	0.02 person* 8 km	US LCI 2021 (NREL), Federal LCA commons
	Collection truck, Bulky waste, City	Collection vehicle, 10t Euro3, urban traffic, 1 liter diesel, 2006	16 km*0.00023 liter/km per kg	EASETECH

	center, Aarhaus, Euro3, DK, 2007			
	VS, C, N degradation USA	Wheel loader, combustion of 1L of diesel, 2008/2011	0.0014 liters/kg*	EASETECH
		SERC Electricity mix	0.01 kWh** per kg	SWOLF
		Polyvinylchloride resin (S-PVC), 1998, RER, ELCD	3.6E(-6) kg per kg***	EASETECH
		NMVOC emissions	1E(-6) kg per kg**	
		Ammonia emissions	7.5E(-6) kg per kg	assume 25:1 C:N ratio for incoming feedstocks
		N2O emissions	1.1E(-5) kg per kg	assume 25:1 C:N ratio for incoming feedstocks
PLA-C, MTB-C, PHA-C, LDPE-C (unique values)	Composting air emissions USA	Emissions from Carbon degraded, see Table 10	99.8% of degraded carbon goes to CO2; 0.02% is degraded into methane but 95% of this portion is then oxidized to CO2	EASETECH
	Distribution of TS after degradation USA	Amount of remaining TS to rejects	See Table 10	
PLA-C, MTB-C, PHA-C, LDPE-C (same for all)	Water content compost		40%	EASETECH
	Compost use (Garden waste in gardens, [NPK + peat subst], substitution profile and air emissions	Average K Fertilizer Average P Fertilizer Peat Average N Fertilizer	-3E(-3) kg/kg compost -3E(-4) kg/kg compost -2.8E(-4) kg/kg compost -4.5E(-4) kg/kg compost	EASETECH
	Water content rejects USA		5%	EASETECH
		Landfill of biodegradable waste	1 kg per kg of rejects	EASETECH

*Obtained data from ACC: 12038.99 tons compost tip per year / 52 = 231.52 tons per week = 210031 kg per week; 80 gallons diesel used per week = 302.8 liters per week
**calculation derived via SWOLF. Major equipment at ACC: screen, loaders, forced aeration (pump)
***26 PVC pipes of ~ 30 feet each = 780 ft of 4 inch PVC; 4 in PVC is ~ 1 kg/ foot = 780 kg; assume 20 year lifetime for system; 39 kg of PVC per year; divided by yearly compost volume

A-3 Landfilling scenarios data for LCI

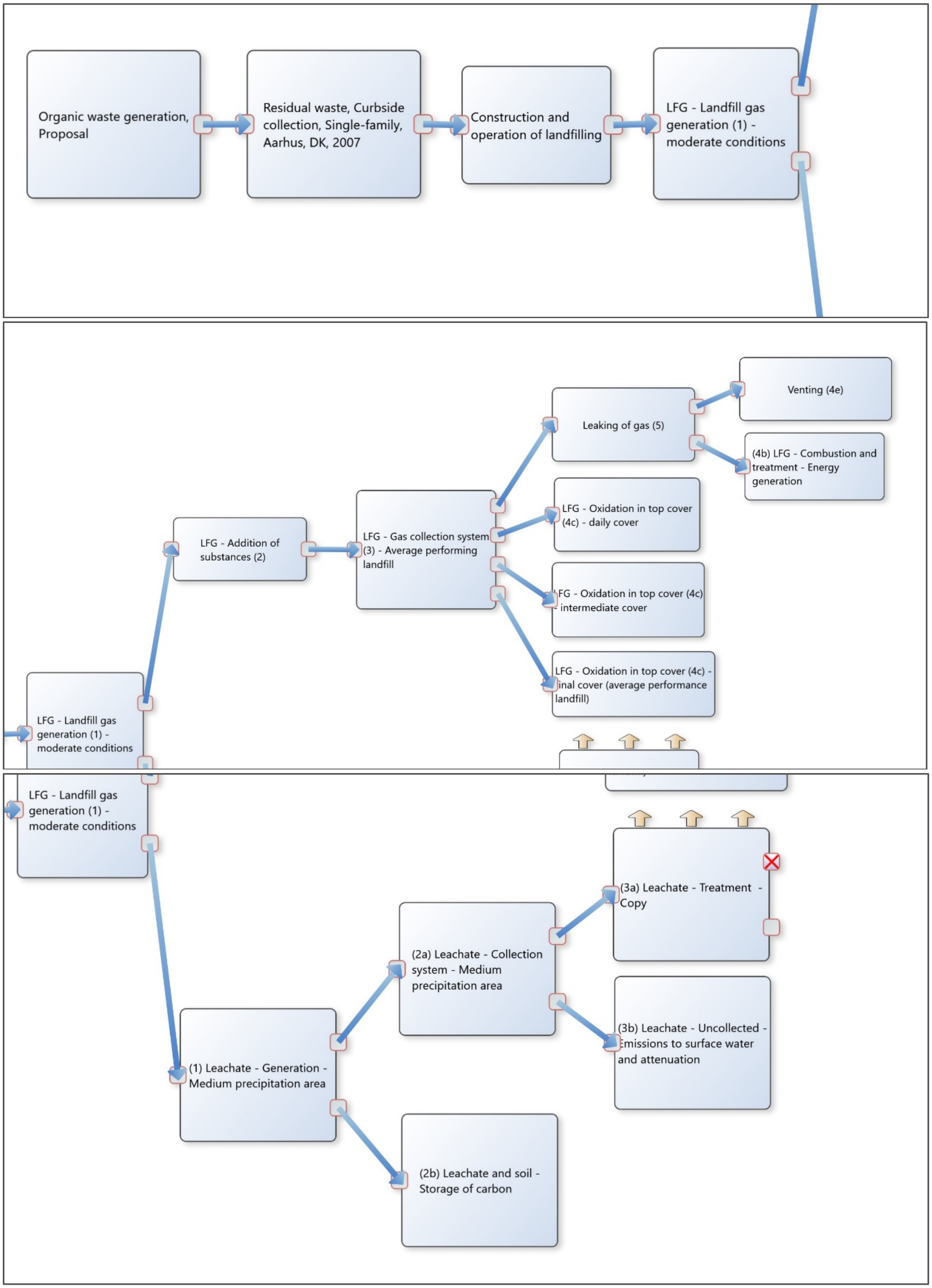

Figure 37 EASETECH Model structure - Landfilling

Table 15. Landfill LCI data detail

Process	Name	Amount and notes	Database
Residual waste, Curbside collection, Single-family, Aarhaus, DK, 2007	Collection Vehicle, 10t Euro3, urban traffic, 1 liter diesel 2006	0.00327 liters/kg	EASETECH
Construction and operation of landfilling	Production and Combustion of Diesel Oil in Truck, EU2,1998	2.02E-4 kg per kg	EASETECH
	Polyvinylchloride resin (S-PVC), 1998, RER, ELCD	1E-05 kg per kg	EASETECH
	Polyethylene high density granulate (PE-HD), 1999, RER, ELCD	0.00023 kg per kg	EASETECH
	Polypropylene fibres (PP); production mix, 2005, EU-27, ELCD	4E-08 kg per kg	EASETECH
	Aluminum, Al (Primary), World average, 2005	5.8E-08 kg per kg	EASETECH
	Steel Sheets (97.75% primary), Sweden, 2008	0.00014 kg per kg	EASETECH
	SERC Electricity mix	0.008 kWh per kg	EASETECH/ SWOLF
	Gravel	0.18 kg per kg	EASETECH
	Clay	0.082 kg per kg	EASETECH
	Copper	9.87E(-9) kg per kg	EASETECH
Landfill gas generation – moderate conditions	k rate time horizon loss of VS related to loss of C bio	0.02 100 years 1.89	assumptions, EASETECH
LFG – addition of substances	Trace gases	incl. NMVOC, Naphtalene, Hg, others sourced from literature	EASETECH
LFG – gas collection system – average performing landfill	Also Leaking of gas; Venting	Based on average US landfill	EASETECH
LFG – combustion and treatment – Energy generation	SERC Electricity mix	-0.25/(3.6*38 MJ/Nm3 CH4) per m3 CH4	EASETECH/ SWOLF
	Heat from natural gas	(-0.6*38 MJ/Nm3 CH4) per m3 CH4	EASETECH
Leachate generation – medium precipitation area	Concentrate, infiltration	Based on average US landfill	EASETECH
Leachate collection system Medium precipitation area and uncollected emissions	99.9% collected first 80 years; 87% collected in next 20 years	Based on average US landfill	EASETECH
Leachate treatment	SERC Electricity mix	0.000443 kWh per kg total	EASETECH
	Process water	3.19E-08 kg per kg total	EASETECH

Leachate and soil storage of carbon	Credits	C bio remaining	EASETECH

A-4 Additional detail on data for degradation and other physical specifications

Table 16: Material data details

Material	**Data point**	**Source and details**
PLA	TS and VS	(Greene, 2018) (PLA straws) TS: 99.59% VS: 94.9% of TS
		(Krause & Townsend, 2016) (PLA cutlery wrapper) TS: 99.5% VS: 100% of TS (PLA straws) TS: 99.7% of TS VS: 100% of TS
		(Kolstad et al., 2012) (PLA pellet – semi crystalline) TS: 99.85% VS:100% of TS (PLA pellet – amorphous) TS: 99.9% VS:100% of TS
		(W. Zhang et al., 2018) (PLA film) TS: 99.6% VS: 100% of TS
	Carbon content	(Kolstad et al., 2012) (PLA pellet – semi crystalline) 52.25% (PLA pellet – amorphous) 50.5%
		(W. Zhang et al., 2018) (PLA film) 51.21%
		(Castro-Aguirre et al., 2017) (PLA film) 49.93 – 50.05% (PLA sheet) 50.0%
	Degradation Composting	(Greene, 2018) (PLA straws) (180 days at 58 C) 91.22%
		(Ruggero et al., 2021) (PLA pellet – rigid)(60 days – 20 thermophilic, 40 mesophilic) 3%
	Landfill C biodegradation	(Greene, 2018) (PLA straw and PLA cup) (20 days at 50 C) 6%
		(Greene, 2018) (PLA ??) (20 days at 37 C) 0%
		(Kolstad et al., 2012)(PLA pellet – semi crystalline)(170 days at 35 C) 0% (PLA pellet – amorphous)(170 days at 35 C) 40% (based on measured methane/theoretical)
		(Kolstad) 390 days at 21 C both were 0%
		(Yagi et al., 2014)(PLA powder)(277 days at 37 C) 29-49%

	Methane potential Landfill	(Greene, 2018) (PLA straw and PLA cup) (20 days at 50 C) 0.02 L/gVS and 0.01 L/gVS
		(Kolstad et al., 2012)(PLA pellet – semi crystalline) 0 (PLA pellet – amorphous) 170 days at 35 C 260 N-liter/kg
		(Krause & Townsend, 2016) (60 days at 55 C) 185–372 mL/g
		(Vasmara & Marchetti, 2016) (98 days at 35 C) 0
		(Vasmara & Marchetti, 2016) (98 days at 55 C) 285 ml/gVS
	Decay rate Landfill	(Kolstad)(170 days at 35 C) (PLA pellet – amorphous) 0.011 per year
	Open Environment	(Greene, 2018) (PLA bottle and PLA bag) (180 days at 30 C in ocean water) <5%
		(Chamas et al., 2020) (PLA bag) 270 microm/yr surface degradation rate on land 16 microm/yr surface degradation rate marine 0.19 yr half life land 3.1 yr half life marine
MaterBi	TS and VS	(Greene, 2018) (Biobag) TS: 93.48% VS: 99.58% of TS
		(Vasmara & Marchetti, 2016) TS: 98.5% VS: 94.5%
	Carbon content	(Vasmara & Marchetti, 2016) 50.64%
	Degradation Composting	(Ruggero et al., 2021)(bags – specified 20% starch, 70% PBAT, 10% additives) 40% ovrsll
		(Mohee, Unmar, Mudhoo, & Khadoo, 2008)(72 days in compost pile) 27% biodegradation by mass loss
	Landfill C biodegradation	(Greene, 2018) (Biobag) (20 days at 50 C) 5%
	Methane potential Landfill	(Greene, 2018) (Biobag) (20 days at 50 C) 0.18 L/gVS
		(Vasmara & Marchetti, 2016) (98 days at 35 C) 33 mL/gVS
		(Vasmara & Marchetti, 2016) (98 days at 55 C) 108 mL/gVS
	Open Environment	(Mater-Bi;, 2018) (ASTM 6691) (180 days at 30 C) 80% biodegradation measured by % conversion to CO2
PHA	TS and VS	(Greene, 2018) (PHA bag) TS: 99.03% VS: 99.99% of TS
		(Gómez & Michel, 2013) (PHA film) TS: 99.4% VS: 90.4% of TS
		(Wang et al., 2018) PHA sheet TS:99.9%

		VS:100% of TS
	Carbon content	(Gómez & Michel, 2013) (PHA film) 50.7%
		(Wang et al., 2018) PHA sheet 58.4%
	Degradation C Composting	(Greene, 2018) (PHA bag) (180 days at 58 C) 94.03%
	Landfill C biodegradation	(Greene, 2018) (PHA bag) (20 days at 50 C) 38%
		(Greene, 2018) (PHA bag) (20 days at 37 C) 95-100%
		(Yagi et al., 2014)(PHB powder)(26 days at 37 C) 92%
		(Wang et al., 2018)(85 days at 38 C) 77.1%
		(Hegde et al., 2021)(40 days at 37 C) 70%
	Methane potential Landfill	(Greene, 2018) (PHA bag) (20 days at 50 C) 0.82 L/gVS
		(Wang et al., 2018)(85 days at 38 C) 483.8 mL/g
		(Hegde et al., 2021)(40 days at 37 C) 384 mL/gVS
		(Hegde et al., 2021)(40days at 52 C, codigestion with food waste – average of ratios* high level of uncertainty) 292 mL/gVS
	Open Environment	(Greene, 2018) (PHA 4100, PHA 2200) (180 days at 30 C in ocean water) 47%, 37% (greater than cellulose at 32%)
		(Pérez-Arauz et al., 2019)(novel PHA film)(80 days at 23 C in soil) 76% mass loss CO2 max 0.2186 mM/mg
		(Gómez & Michel, 2013)(660 days at 20 C in soil) 69.2% carbon loss
		(Dilkes-Hoffman, Lant, Laycock, & Pratt, 2019) Marine biodegradation rate of 0.04 – 0.09 mg/day/cm^2 Straw would take 0.3 to 0.7 years to completely degrade
		(Wang et al., 2018)(148-195 days at 25 C marine) - sheet k 0.004 per day 55.3% +/- 38.3% biodegradation
		(Wang et al., 2018)(148-195 days at 25 C marine) - powder k 0.019 per day 88.6% +/- 0.6% biodegradation
LDPE	TS and VS	(W. Zhang et al., 2018) (LDPE film) TS: 100% VS: 99.8% of TS
	Carbon content	(W. Zhang et al., 2018) (LDPE film) 84.78%
		(Castro-Aguirre et al., 2017) (LDPE/LLDPE film) 86.63%
	Degradation C Composting	(Greene, 2018) (LDPE Clingwrap) (180 days at 58 C) 1.7%

	Open Environment	(Greene, 2018) (LDPE bag) (180 days) <5%
		(Chamas et al., 2020) (Plastic bag) 11 microm/yr surface degradation rate on land 15 microm/yr surface degradation rate marine 4.6 yr half life land 3.4 yr half life marine

A-5 Additional LCIA results

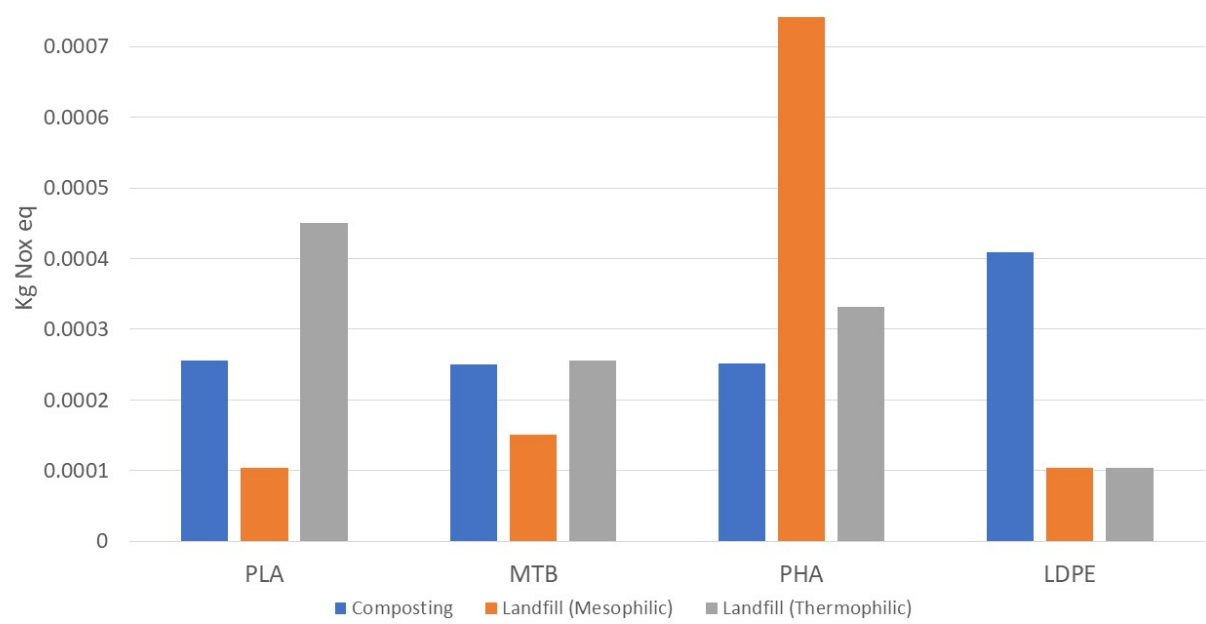

Figure 38: Photochemical oxidant formation Human Health midpoint

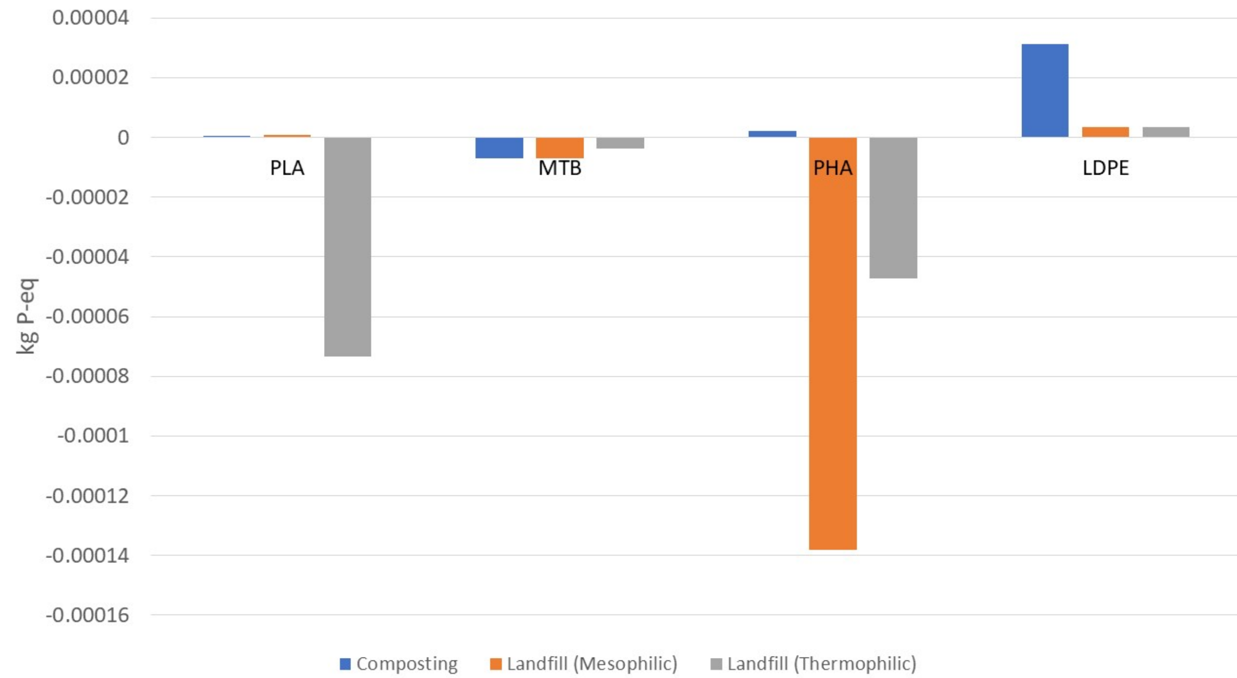

Figure 39: Freshwater eutrophication midpoint

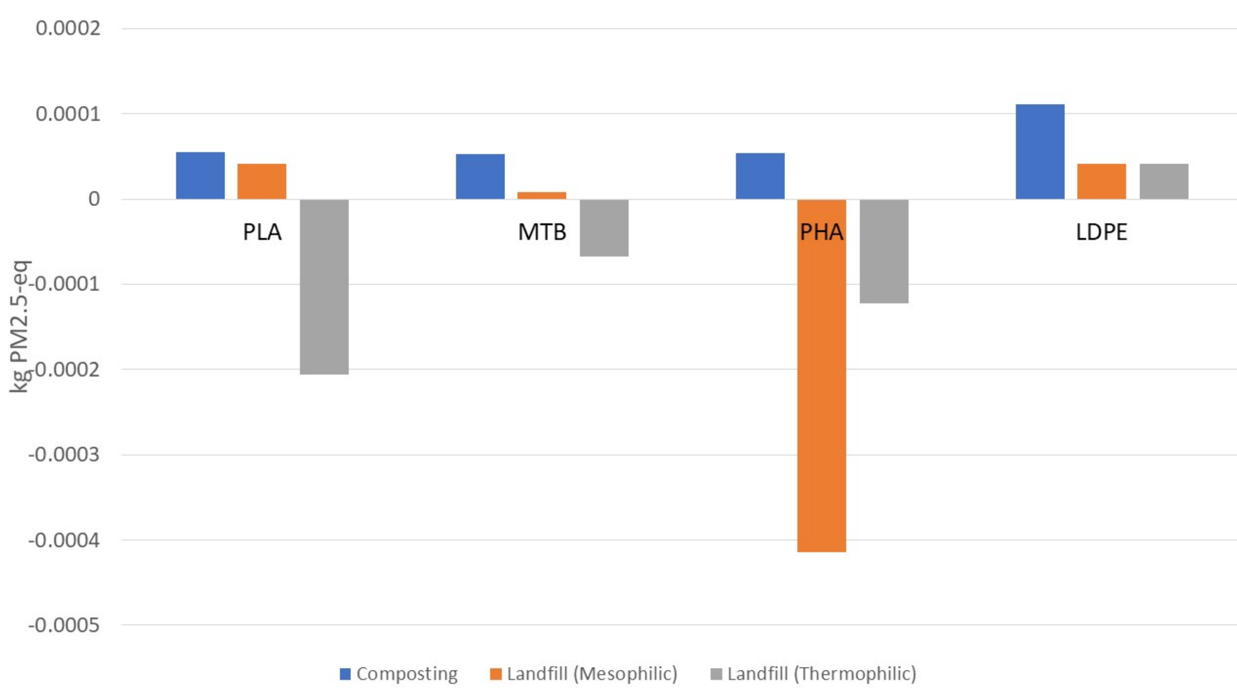

Figure 40: Particulate matter formation midpoint

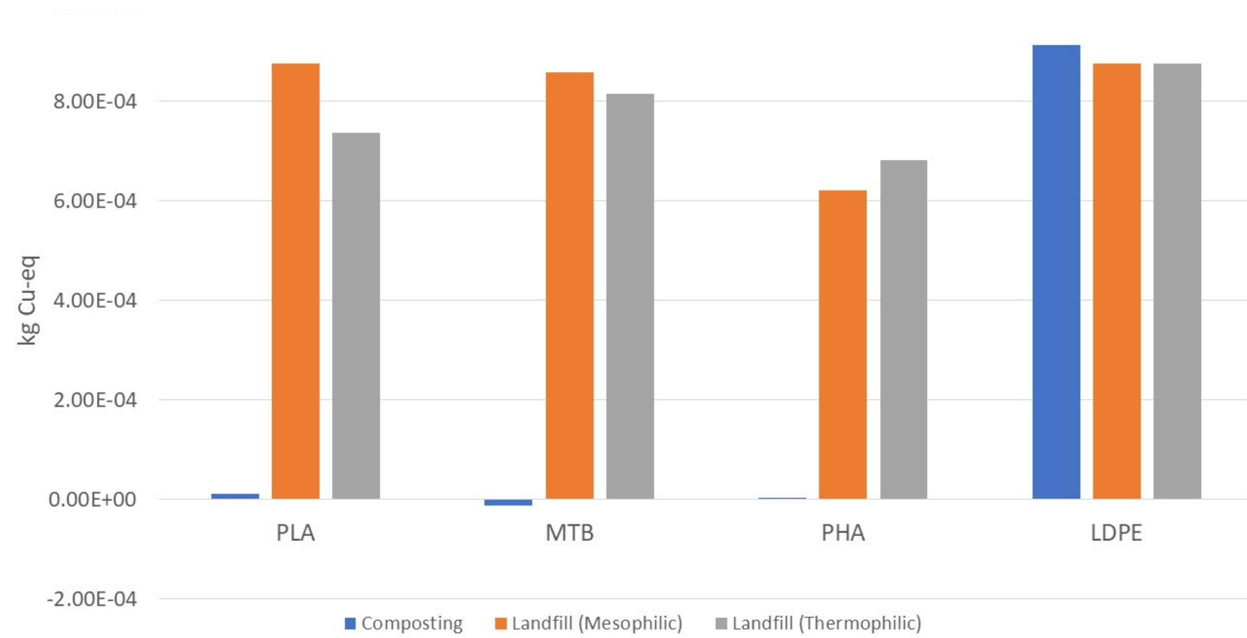

Figure 41: Mineral Resource Scarcity midpoint

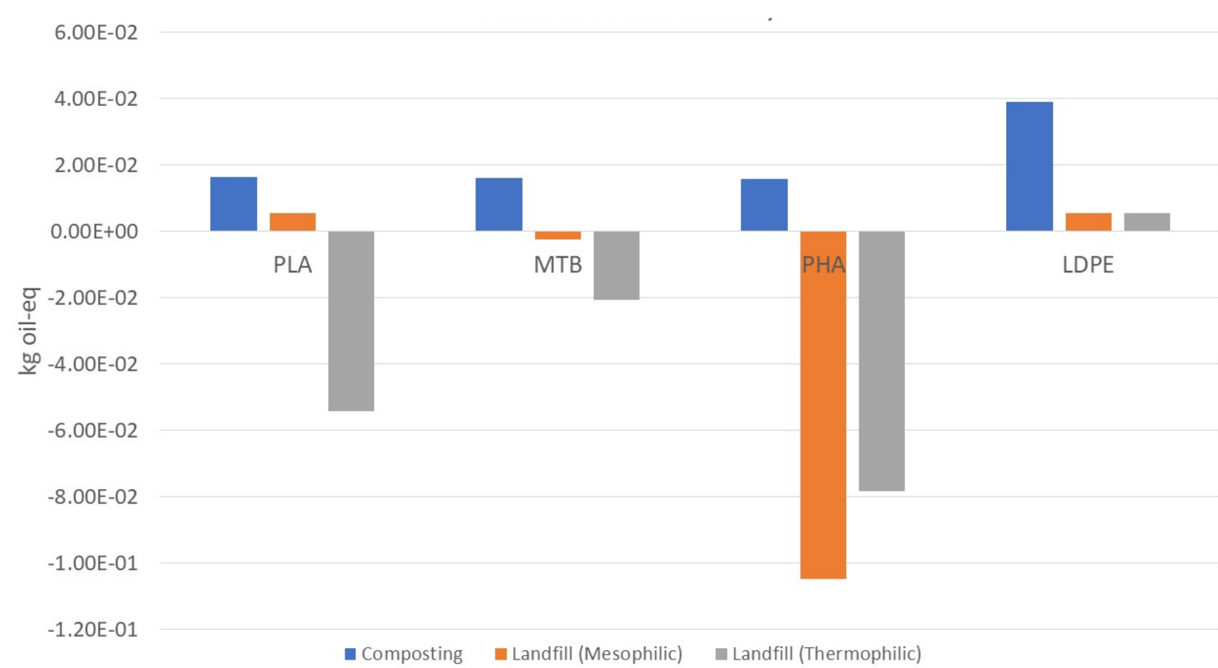

Figure 42: Fossil Resource Scarcity midpoint