Degradable Plastics and Solid Waste Management Systems

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Degradable Plastics and Solid Waste Management Systems

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November 2013
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Abstract

Plastics, which are woven into the fabric of modern life, have consequential impacts on the environment. Many of these are associated with end-of-lifetime processes, and include chemical contamination of the environment and effects from litter. Plastics also complicate waste management processes, causing contamination in composting operations, and having poor recovery rates through recycling. Plastics that are not as biologically recalcitrant, that decompose when use is done, have been perceived as solutions to at least some of these problems. The first generation of degradable plastics did not meet marketing claims; some of the more recent formulations, partly as a consequence of third party certifications, are more compliant. However, many plastics that are labeled as “degradable” do not decompose very readily, and it is not clear that litter will be diminished to any great degree through their use. In addition, because not all plastics are or will be degradable, user confusion is and will be common. Multiple formulations mean not all degradable plastics address compost contamination, and most degradable plastics do not address other problems associated with plastics waste management. Therefore it is not clear that degradable plastics constitute a major technological advance; in fact, overall they may be more harmful than helpful.
1. Introduction

Plastics, especially consumer plastics, are integral elements of modern life, and have been in use for over 150 years (Friedel 1993; Andrady and Neal 2009). Their ubiquity is increasing; one estimate was that 300 million tonnes of plastics were produced worldwide in 2012 (Rochman et al. 2013). The growth of plastics use is further reflected in US Environmental Protection Agency US disposal estimates: in 2009, 30 million tons of plastics were disposed (12% of US municipal solid waste), compared to 1960, when less than two million tons were disposed (about 1% of the US waste stream) (USEPA 2010). Plastic materials can be created for a near infinite variety of purposes, but packaging and single use consumer products capture most of the general public’s attention (e.g., Sparke 1993; Livesey 1999; Viehover 2000). One estimate is such items are 35%-45% of all plastics production (Chiellini et al. 2006). This implies that as much as 100 million tonnes of single use plastics are made and disposed worldwide each year.

Plastics have replaced paper and other materials because they are superior in terms of strength, durability, stability, lightness, and impermeability (Andrady and Neal 2009). These same properties, however, impede their disappearance in the biosphere, creating continuing concern over environmental impacts (Thompson et al. 2009; Rochman et al. 2013). Plastic litter, especially in aquatic environments, can have noxious impacts on biota (Gregory 2009). Chemical variation in resin types can make reuse and recycling difficult (Stein 1998; Kuswanti et al. 2003; Goodship 2007). Conventional plastics may require decades (or longer) to degrade (Gruenwald 1993; Searle 2003; Koutny et al. 2006; Ammala et al. 2011), and the degradation process may release additives and byproducts that pose threats to the health of organisms (including people) (Talsness et al. 2009) to the degree that there has been a call to declare plastics hazardous materials (Rochman et al. 2013).
Negative aspects of plastics often continue as they are managed through solid waste processes. Plastics cause problems at composting plants; collection of yard waste in plastic bags causes residual plastics contamination at yard waste composting sites, and plastic disposable utensils and other service ware complicate efforts to create clean compostable waste streams for food and MSW composting (Katz 1993; Wiles and Scott 2006; USEPA 2010). Chemical contaminants associated with plastics are often released to the environment through waste management pathways. Additives that have sparked recent (and growing) concern, such as bisphenol A (BPA) and phthalates (Meeker et al. 2009), have been found in landfill leachates (Vandenberg et al. 2007; Zhang et al. 2009), reaching the environment if there are liner system leaks. Another landfill leachate route to the environment is when leachates are treated at waste water treatment plants and effluents are discharged, as not all of these chemicals are removed through standard treatment (Auriol et al. 2006; Barnabe et al. 2008; Dargnat et al. 2009). Plasticizers that are removed in sewage treatment contaminate the resulting sewage sludges (Carbella et al. 2006; Barnabe et al. 2008; Dargnat et al. 2009; Barnabe et al. 2009), and the trend toward greater reuse of sludges means wide distribution of them to agricultural soils (Kinney et al. 2006; Barnabe et al. 2009). Incineration of chlorinated plastics has been linked by some to enhanced dioxin generation (Thornton 2000; Belliveau and Lester 2004); polyvinyl chloride (PVC), for instance, is more than 55% chlorine by weight (Scheirs 1998), and so may be a substantial source of chlorine during combustion.

Litter (the improper disposal of goods) is an especially noxious problem due to plastics (Wiles and Scott 2006; Barnes et al. 2009). Plastic bags are extremely mobile, with their high surface area to weight ratio creating sail-like materials (FMI 2008). Most plastics are less dense than water and are hydrophobic, so that they can be transported long distances after reaching
water bodies because they float and do not settle (Thompson et al. 2004; Ryan et al. 2009; Browne et al. 2010). Although, like all organic matter, plastics are susceptible to damage from UV radiation, the polymer structure of plastics rarely degrades entirely due to such effects (Gruenwald 1993; Hakkarainen and Albertsson 2004); in addition, floating plastics may gain fouling biofilm that inhibits further exposure to sunlight (Gregory and Andrady 2003). Few microorganisms can use plastic polymers for sustenance, especially when the polymers are intact (Gruenwald 1993; Witt et al. 1999). Thus, plastic litter, especially in marine settings, is notably persistent as few other litter materials are, and often remains visible forever, seemingly (Derraik 2002; Moore 2008). Entanglement and envelopment in plastic debris affects organisms (Gregory and Andrady 2003; Gregory 2009) and floatable material can serve as simulacra of prey, so that surveys of charismatic marine species often document ingestion of plastic (Derraik 2002; Gregory and Andrady 2003; Gregory 2009). The visible portion of litter may not be the greatest problem, however, as a greater mass of plastic is present in the “microlitter” fraction (Thompson et al. 2004). Organic carbon plastic chains are attractive sorption sites for other organic molecules, including persistent organic pollutants, and so may serve as concentration sites for contaminants of concern (Teuten et al. 2009). Marine plastics pollution has been documented to have harmed individuals from 267 species, including 86% of sea turtles, 44% of seabirds, and 43% of marine mammals (Laist 1997), and impacts may be underestimated as many affected organisms sink or are consumed by predators (Wolfe 1987). Terrestrial litter management is expensive and often difficult (Mid Atlantic Solid Waste Consultants 2009). Marine litter is only rarely addressed; one program was developed in New York Harbor after several notable beach wash-up episodes (Swanson and Tonjes 2001).
Solutions have been proposed to address the global challenges of plastic wastes. One simplistic answer is to avoid plastic use altogether. The important role played by plastics in modern materials (Katz 1993) makes this difficult to implement entirely. Minimization of particular plastics use has been sought, so that some packaging uses (primarily polystyrene) were banned in locations across the US in the 1990s (Swanson et al. 1993), or were voluntarily foresworn (e.g., McDonald’s clamshells, see Roberts and Dennison 1994). Plastic bags have been legislated against in various places, such as in Ireland in 2002 (Convery et al. 2007). The plastics industry has responded by establishing and supporting recycling programs (Fisher 2003; Kuswanti et al. 2003; Goodship 2007). Recycling diverts plastics from disposal, but rates for most plastic items remain low, especially when compared to other items in commerce such as newspaper or aluminum containers (Davis and Song 2006; Hopewell et al. 2009; USEPA 2010). Packaging product stewardship programs (where manufacturers and/or distributors become responsible for the end-of-life of packaging), since plastics constitute a major element of packaging and are often perceived as the constituents causing the most problems (Viehover 2000), have been adopted in Germany (Fishbein 1994), generally across the European Union, and in Japan, Taiwan, South Korea, Brazil, and Peru (Selke 2003), and in British Columbia, Nova Scotia, and Ontario provinces, Canada (personal communication, H. Sanborn, Executive Director, California Product Stewardship Council, 10 May 2011). Most recently, a position paper suggested that because of the sum of impacts associated with their use and, especially, their mismanagement, plastics should be classified with other products and chemicals that cause great harm to people and other organisms, and receive an official label as a hazardous product (Rochman et al. 2013).
One means of addressing some of these issues has been the production of plastics that are intended to degrade once their service life is over (Stevens 2002). Degradable plastics are intended to address litter problems (Koutny et al. 2006), and to coexist better with composting efforts (Song et al. 2009); degradable plastics may also generate benefits when landfilled (Ress et al. 1998), although it is unclear if degradation is always optimal in landfills (Barlaz 1998). The compatibility of degradable plastics with conventional reuse and recycling programs remains a problem (Al-Malaiki et al. 1995; Scott and Wiles 2001; ExcelPlas Australia et al. 2004; Goodship 2007), and there has been little consideration of potential interactions with energy recovery and other advanced waste processing systems.

Degradable plastics clearly are designed to address the end-of-life of plastic products, and intend to reduce the environmental impacts associated with their use and management and mismanagement. Are degradable plastics compatible with current waste management practices? Can they serve as an element in future, more sustainable materials management systems? We address these questions by surveying the development of degradable plastics, reviewing many degradable plastics marketed today, and then considering whether these products have appropriate specifications that are either compatible with or improve current and possible waste technology systems.
2. History of Degradable Plastics

Synthetic polymers are generally resistant to most degradation over human-scale time frames, which is an important characteristic for their use. However, they do undergo “weathering”: the sum of chemical reactions, such as oxidation or hydrolization and degradation from radiation (Searle 2003), as particular bond lengths correspond to the radiation wave length, and absorb energy, destabilizing the atomic bond through Norrish I or Norrish II reactions (Gilead 1985). They can be consumed by organisms, too, although most polymers are not readily digestible (Witt et al. 1999; McCarthy 2003). However, it must be understood that natural polymers are common, such as lignin and coal; with very few exceptions, all polymers are capable of being degraded by natural processes, although it may take a very long time (Steinbuchel 1995; Scott 2000; Scott and Wiles 2001). It has been said that unweathered polyethylene is “essentially a non-biodegradable material” (Koutny et al. 2006), but, in the longest view, all plastics are in some sense “degradable.”

Plastics manufacturers use additives to enhance mechanical or optical properties of polymer types. Stabilizing additives include hindered phenol antioxidants, thioethers, and metal chelates, which reduce oxidation and hydrolization reactions by either competing for reactants or blocking reaction sites. Ultra-violet (UV) light stabilizers, especially carbon black, convert UV energy to heat preventing the energy from breaking atomic bonds; many other specialized compounds are also used to retard degradation (Gruenwald 1993). Many plastics degrade under visible light, which results in “yellowing” (Searle 2003). Halogen containing polymers, such as poly vinyl chloride (PVC), are subject to loss of the halogens under high temperature or bright light; metal compound additives suppress these reactions. Adding metals to polymers increases concerns that their release could have environmental effects, and also affects the resulting
material’s electrical conductivity. A common additive to PVC insulators is lead, since lead salts are insoluble and so do not contribute to electrical conductance (Gruenwald 1993).

Intended degradation must only occur at the proper time under the right conditions (Gruenwald 1993; Scott and Wiles 2001). Typically, one of two differing strategies is pursued: stabilizers can be omitted, or additives can be included to promote desired reactions. Design choices need to consider particular polymer properties and uses. For instance, some plastics are especially resistant to UV degradation, such as acrylic polymers and polyolefins. However, if polyolefins are oxidized, the resulting carbonyl groups are susceptible to UV absorption and bond scission. Thus, photodegradable polyolefins can be synthesized by adding carbonyl groups. The compounds do not degrade indoors because UV light is generally blocked by glass. The carbonyl groups are reactive when exposed to full daylight, and so the overall polymer is cleaved (the first step in eventual degradation of the product) (Gruenwald 1993).

Degradation potential of polymers is usually tested in laboratory experiments that simulate long exposure times. These processes do not exactly match environmental conditions, and the acceleration of the degradation processes by various manipulations in order for experiments to be concluded timely means that determinations of when reactions occur under ambient conditions are often inexact. The closer experiments mimic environmental conditions, the better the likelihood of timing degradation effects correctly (Searle 2003), although careful bench-scale tests in at least one instance considerably over predicted degradation measured in field experiments (Farrell et al. 2001). Laboratory results can lead to incorrect descriptions of degradation potentials, or widely varying estimates of environmental persistence. Thus, many manufacturers claim their products undergo reactions faster or more completely than they actually do. Contrarily, those observing products which remain more intact
in the environment than product specifications outline then fear that these products will remain undegraded for thousands of years or more (Swanson et al. 1993; Belliveau and Lester 2004).

In the late 1980s, several US plastics companies began to market products that were “degradable”: they were intended to last in the environment for time periods of days-weeks-months – something not well-defined, but certainly less than life-spans of normal plastics (Gross and Kalra 2002). Degradation meant the loss of properties, not necessarily the total elimination of polymeric structures. So, these kinds of degradable plastics might lose physical strength and integrity faster than standard plastics. To achieve this, transition-state metals (Gilead 1985), carbonyls, and carbon monoxide groups (Iwaki 1975) were inserted into some polymers, creating greater photosensitivity, and degradation was expected to continue enough so that the remaining fragments might be consumable by micro-organisms. A molecular weight of about 5,000 was thought to be an important threshold (Scott 1973), although direct proof of microbial consumption of polymer carbon has been a difficult task (Albertsson and Karlsson 1988; Witt et al. 1999).

Because UV-sensitive plastics did not always meet consumer expectations of “disappearing” after use (Krupp and Jewell 1991), other approaches, such as starch insertion into polymer chains, were undertaken (Breslin and Swanson 1993). These plastics were commonly made into films – both for “industrial” use (such as agricultural weed barriers and mulch retainers) and consumer products (mostly as larger bags, such as for garbage cans). Some molded products such as bowls and cups were also made. The degradable formulations lost mechanical and physical properties faster than standard plastics, but generally failed to crumble into small or microscopic pieces in “reasonable” amounts of time (seasons to a year) (Krupp and Jewell 1991; Breslin and Swanson 1993). They thus lost favor with consumers, who did not appreciate the
fine distinction made by manufacturers that loss of integrity was “degradation.” Scott (2000; Scott and Wiles 2001, Wiles and Scott 2006) has argued this standard is not fair since many naturally occurring organic materials (especially wood and rubber) do not degrade rapidly either. This argument has not resonated with either the public or regulators; for instance, CSU Chico (2007) suggests instead that “biodegradable” should mean the substance is consumed by microorganisms, and that within 180 days the process will be completed, leaving no “small pieces or residues” behind.

An alternative to modifying petroleum-based plastics is to make plastics from natural polymers that are commonly used by organisms as food, such as starch or cellulose (Song et al. 2009), with the assumption that degradation is then likely to happen. These formulations have had performance issues. Cellulose polymers lose important functionalities before the solid melts, for instance, which limit their utility as plastics (McCarthy 2003). Cellophane, the best-known cellulose “plastic,” is strong but tears easily when lightly damaged. Starch is somewhat better, but tends to crystallize; its high water content makes its workability in manufacturing difficult (Davis 2003), so that starch-based plastics tend to be brittle (Wang et al. 2003). Starch-based products, often labeled as TPS (thermoplastic starch), are available; Earthshell is one prominent brand (McCarthy 2003). Generally, usable plastic products have been realized with these two base compounds by creating mixtures with synthetic polymers (Gross and Kalra 2002) or other degradable resins, such as poly-lactic acid (PLA) (Wang et al. 2003; Schwach et al. 2008). Starch-based plastics have consistently been found to degrade as expected (e.g., Breslin 1998).

Confusion has been further created by the development of industrial biotechnologies that allow plant and other non-petroleum sources of carbon to serve as the basis of plastics (and other products) (Bomgardner 2012). Coca-Cola recently announced that it would seek to use 100%
plant-based plastics for its bottles (Tullo 2012), and Heinz, too, is seeking to use these kinds of products (Reish 2012). These products, although non-petroleum, do not have any special degradability features. Production rates were in the vicinity of 300,000 tonnes in 2010 (Darby 2012).

Bacterially-generated monomers, such as lactic acid and hydroxyalkonates, have achieved better degradation results. These monomers are polymerized to produce the plastics poly-lactic acid (PLA) and polyhydroxyalkanoate (PHA) (Stevens 2002). These plastics generally meet compostable standards (see just below), with polymer chain breakdown often initiated by a temperature signal (Farrington et al. 2005). Scott and Wiles (2001) describe these polymers as “sitting on the knife-edge” between readily consumable polymers like starch and cellulose that have little technical utility as plastics, and conventional polymers that have good plastics attributes but poor degradability.

Certain petroleum-based plastics are marketed as being degradable. Many are conventional plastics with bacterial plastic or starch inserts, but others are modified with metal or other degradation prompters (Scott and Wiles 2001). Some of these polymers include polybutylene succinate (PBS), polycaprolactone (PCL), polybutylene succinate coadipate (PBSA) copolymers, polybutyrate adipate terephthalate (PBAT), adipic acid aliphatic and aromatic copolyesters (AAC), modified polyethylene terephthalate (PET) (Reverte and Biomax brands), modified polyethylene (PE) (TDPA and Totally Degradable Plastic, Addiflex, Degrade, ECO, PDQ, Bio-Solo, Reverte, Biobatch, and Entec brands), modified polypropylene (PP) (Reverte brand), modified poly vinyl chloride (PVC) (BioSmart), polyvinyl alcohol (PVOH), ethylene vinyl alcohol (EVOH), and ketone carbonyl additive packages used as a copolymer (Ecoylte brand) (ExcelPlas Australia et al. 2004, Ammala et al. 2011). All of these are reported
to generally not meet compostable standards (see just below) (Darby 2012), although at least two of these polymers have been found to degrade in compost (Ammala et al. 2011).

After the initial rush of enthusiasm for degradable plastics in the 1980s and early 1990s, and the resulting consumer backlash when product degradation properties did not meet expectations, degradable plastics production hit a lull. Output grew again in the late 2000s, with one estimate being 300,000-400,000 tonnes sold per year (Song et al. 2009) (note that Song et al. 2009 estimated this was 0.2% of all plastics production, implying world-wide plastics production of 200 million tonnes, 50% less than reported by Rochman et al. 2013).
3. Degradable Plastics Labeling

The failure of early biodegradable plastics to degrade as completely as expected has led to refined industry product descriptions so that degradable expectations are met by products (Pagga et al. 1995; Krzan et al. 2006). These voluntary standards generally specify definitions, testing guidelines, and acceptable advertising terminology (Kale et al. 2007), with the intent of creating consistency, accountability, and reliability of behavior across different product lines. Different but similar approaches have been put in place in the US, Germany, Japan, and the European Union, and an international code has been developed by the International Organization for Standardization (ISO) (Krzan et al. 2006).

The American Society for Testing and Materials (ASTM) promulgates acceptable usage through Committee D20.96, “Environmentally Degradable Plastics and Biobased Products,” leading to two ASTM standards addressing biodegradable plastics in composting environments: D6400 (specification for compostable plastics) and D6868 (specification for biodegradable plastics used as coating on paper and other compostable substrates) (BPI 2011). These standards define compostable plastics operationally, based on conditions found at municipal and industrial compost facilities (Krzan 2006), according to three tests:

1) conversion to CO₂ by organisms found in compost at an acceptable rate;

2) fragmentation; and

3) a determination that the resulting compost can support plant growth (including elemental testing to meet standards for metals content) (Goldstein and Olivares 2007).

ASTM has also developed the standard D7081 for non-floating biodegradable plastics in the marine environment which is used for biodegradable plastics that are designed to biodegrade in marine waters and sediment. The primary European standards (from the Comite Europeen de
Normilisation), EN 13432, as well as the companion standards (EN 14045, EN 14046, EN 14047, EN 14048), are similar to D6400 and D6868, and require that compostable plastics set in an aqueous biotic environment be substantially (>90%) converted to CO$_2$ and biomass within six months with visual disintegration, and result in a product that is “recognizably” compostable-degradable by the compost product “end user” without toxic by-products (Scott and Wiles 2001, Wiles and Scott 2006, Krzan et al. 2006).

Certification programs are intended to guarantee certain materials or products meet standards (Krzan et al. 2006; Kale et al. 2007). In the US, the Biodegradable Products Institute (BPI) and the US Composting Council created the Compostable Logo program (CSU Chico 2007), so certified manufacturers can use a product or product packaging logo to identify a compostable product to consumers, and, potentially, help ensure the product receives appropriate end-of-life management. Many “degradable” plastic products cannot meet compostable standards.
4. Current Degradable Resins

Modern iterations of degradable plastics are used in packaging, disposable food utensils and tableware, bags, mulch films, and diapers (Gross and Kalra 2002; Krzan et al. 2006). Only a few durable goods are made from degradable plastics, as it can be difficult to suppress degradability until disposal for long-lived products (Song et al. 2009).

Two resins used to make plastics conforming to certifications for compostable plastics that have been tested to show good degradability at compost sites and are manufactured in substantial quantities are poly-lactic acid (PLA) and polyhydroxyalkanoate (PHA) (Mohee and Unmar 2007). They are typically manufactured as pellets, which can then be used to create a variety of products, often with the use of additives to achieve specific materials properties (Goldstein and Olivares 2007; BPI 2011). Other materials that are also marketed as degradable plastics will be discussed, such as oxo-degradable plastics and other modified polymers.

4.1 Poly-Lactic Acid (PLA)

PLA has the largest share of the US bioplastic market due to its many applications, such as thermoformed cups and containers, forks, coatings for paper cups, and candy wrappers (Farrington et al. 2005, CSU Chico 2007). PLA is produced in a complex, two-step fermentation and chemical polymerization process. Lactic acid is generated by bacterial fermentation of various carbohydrates (often from agricultural byproducts, such as glucose from corn starch or sucrose from cane sugars). Next, the lactic acid is oligomerized and then dimerized to make a cyclic acid monomer, which is polymerized to yield PLA (Garlotta 2001).

PLAs have elastic properties that allow them to replace commodity plastics for packaging or some film uses (Vert et al. 1995). However, PLA cannot be simply substituted into existing
manufacturing processes in place of standard polymers because PLA seals, forms, and flows
differently than conventional plastics (Yepsen 2009b).

In compost piles, moisture and heat attack PLA polymer chains, splitting them apart
through hydrolysis, creating smaller polymer fragments, and, potentially, reducing the fragments
to lactic acid monomers. Microorganisms can consume smaller polymer fragments and lactic
acid (Farrington et al. 2005).

4.2 Polyhydroxyalkanoate (PHA)

Polyesters of hydroxylkanoates (PHAs) are a broad class of compounds naturally
synthesized by more than 300 species of bacteria as intracellular carbon and energy storage
compounds (Steinbuchel and Valentin 1995; Berlanga et al. 2006). PHA structure, physio-
chemical properties, monomer composition, and the number and size of granules vary depending
on the production species (Anderson and Dawes 1990; Ha and Cho 2002). PHAs accumulate in
the cytoplasm of bacterial cells under conditions of limited nutrients; the bacteria use PHAs as
carbon and energy sources when the nutrient limitation conditions end (Lee 1996). A wide
variety of substrates may be used to produce PHAs, especially agricultural materials such as
starches and sucrose (Reddy et al. 2003). To produce PHA commercially, unfavorable growth
conditions (limited nitrogen, phosphorus, or magnesium) are induced for particular bacteria,
causing them to synthesize and store PHAs (Suriyamongkol et al. 2007).

The wide diversity of potential PHA monomers results in a broad spectrum of polymers
with many different properties (Suriyamongkol et al. 2007). Extracted PHAs are processed
similarly to traditional plastics since specific PHA monomers confer specific properties (Byrom
1987). Outputs include both flexible and durable plastics, which are used primarily for products
such as containers, bottles, razors, and food packaging. PHA is expensive, however, costing five
to ten times traditional plastics (Suriyamongkol et al. 2007). The simplest and most common PHA is polyhydroxybutyrate (PHB) (Leja and Lewandowicz 2009).

PHA plastics are attacked by microorganisms that secrete PHA depolymerizer, and most products take three to nine months to degrade (Jendrossek 2001; Suriyamongkol et al. 2007). These organisms naturally occur in soil, compost sites, and marine sediments (Reddy et al. 2003).

4.3 Other Marketed Degradable Resins

Polyolefins (commonly, polyethylene and polypropylene) can have quicker degradation if modified by adding transition metals/compounds (iron, cobalt, manganese, ferrocene, and titanium and zinc oxides), and other “pro-oxidants” (ketone copolymers, alkaline earth or ammonium oxy-hydroxy groups, alcohols and esters, benzophenone, pyrone rings, polyisobutylene, amines, and peroxides) into the polymer backbone. This results in UV or heat-initiated oxidation of the polymer (Ammala et al. 2011).

Oxidation of the polymer theoretically changes the plastic from hydrophobic to hydrophilic (Scott and Wiles 2001), and makes the compounds digestible by microorganisms, if molecular weights of the fragments are less than 5000 Daltons (Da) (Ammala et al. 2011), although some polyethylene has been reported to be consumed by fungi at weights from 4 - 28 kDa (Yamada-Onerdera et al. 2001). Experiments reported by Koutny et al. (2006) showed that shortened PE chains (up to 100 kDa, although often much shorter) served as substrate for inoculated bacteria (either pure strains or extracts from environments such as compost piles), as measured by either gas emissions or changes in the plastics. Placing shortened PE chains in environmental conditions conducive to degradation (forest soils, compost piles) resulted in continuing chain size reduction and CO₂ off-gassing.
Koutny et al. (2006) were not convinced that the mechanisms for biotic decay have been well-described. Despite finding some evidence of decay for longer polymers, they have endorsed the view that reduction to ~5 kDa is necessary. Braunegg and Haage (2001), using analogies to degradation of alkanes, thought it highly unlikely that chains longer than 44 carbon molecules would be susceptible to microbial consumption because the molecules are too large to pass into a cell, and no ligases exist for these anthropogenic polymers. They noted that polyethylene molecules of 1-5 kDa would have 70-350 C-C bonds, and so discounted reports of biodegradation of PE at 5 kDa. Thomas et al. (2012), while agreeing that fragmentation of oxidizable plastics occurs in the environment (at time frames of 2-5 years in the UK), discounted reports of subsequent biodegradation as unproven. Mohee et al. (2008), therefore, suggested that fragmentation (“degradation”) should be distinguished from microbial uptake (“biodegradation”).

Polyolefins require a mechanism for the initiation of degradation; this is said to be the rate-determinant for the degradation process. The rates of degradation initiation can be controllable by balancing inclusions of oxidant and anti-oxidant compounds in petroleum-based polymers (Wiles and Scott 2006). Encouragement of biological degradation is often attempted by blending a conventional, petroleum based polymer with starch. Many of the degradable plastic products that use petroleum-based plastics have up to 50% starch content. Conventional petroleum-based polymers that are sold mixed with large amounts of starch to either create degradability or to reduce costs of the polymer include PBSA, PBAT, AAC, and Biomax brand modified PET (ExcelPlas Australia et al. 2004). PHB, one of the bacterial PHAs generally identified as a compostable plastic, can be mixed with polyethylenes as films or bottles (PBAT). A test of film made with PHB and mixes of PHB and TDPA found that soil burial for two
months resulted in measurable decreases in plastic properties, which have been associated with chain length reductions. These effects were greatest when the samples had been heated prior to burial (Martelli et al. 2009).

One exception to the relative lack of biodegradability of polyolefins (see below) appears to be AAC (adipic acid aliphatic and aromatic copolyesters) produced by BASF. One test found they met the German standards for biodegradation, based on CO₂ evolution after burial in a natural medium. The rate of CO₂ production of shredded plastic in compost was measured and approximately 95% of the carbon in three samples was converted to CO₂ over 100 days, at a slightly slower rate than cellulose (Witt et al. 1999). In a laboratory experiment, an artificial compost medium was inoculated with AAC powder and a microorganism isolated from compost for 21 days. At that point no polymers were detectable – only monomers that compose the AAC. A film of AAC under the same exposure conditions visually fragmented after four days (Witt et al. 2001). It is thought that extracellular enzymes produced by naturally occurring fungi and bacteria cause the initial cleavage of the polymer, allowing for microbial uptake (Witt et al. 1999). CSU Chico (2007) reports that the Ecoflex AAC products have been certified under the ASTM and European standards.

Polycaprolactone (PCL) mixes well with other polymers, and this allows it to be added to standard polymers to assist in their degradability. It is reported to degrade “readily” through exposure to environmental micro-organisms (Woodruff and Hutmacher 2010), especially when blended with starches, although this means losses in plastic properties (Koenig and Huang 1995). A 12-day test in an artificial compost environment resulted in complete disappearance of a pure PCL strip of compost bag; starch-synthetic mix and synthetic blend varieties had substantial mass losses and noticeable physical changes (Day et al. 1997). In an extensive series of
laboratory and field testing, a PCL bag formulation was found to have mixed degradability; it never degraded entirely as did some PLA and PHA bags, but it did better than polyethylene mixes. Overall, its performance was equated to kraft bags (Farrell et al. 2001). PCL first was used as a common dissolvable drug delivery implant beginning in the 1970s, but degradation times of years in animals and humans meant it was supplanted by other more readily degradable compounds. It is currently seeing more use in tissue implants, where it serves as a temporary lattice to enable the body to regrow specific tissues (Woodruff and Hutmacher 2010). Because PCL is only produced by Union Carbide, one brand (Mater-Bi) switched to other formulations (unspecified) around 2001 (ExcelPlas Australia et al. 2004). Testing of the new formulation showed more than 25% mass loss after 72 days of composting, and mixing with sludge to create anaerobic conditions resulted in gas generation rates that were half of those generated from cellulose, after 32 days (Mohee et al. 2008). CSU Chico (2007) reports that Mater-Bi materials are certified under the ASTM and European standards, and by BPI.

The Korean government has encouraged manufacturers to use PCL-starch blended or PBS plastics for retail and garbage bags. Laboratory testing of degradation of these bags under aerobic and anaerobic conditions showed good degradation rates for the starch mixtures, as measured by gas generation rates, but slower degeneration of the PBS (judged to be too slow for effectiveness for compost applications). Both kinds of bags were physically degraded but still recognizable after 90 days burial in a landfill (Cho et al. 2011).

TDPA is aggressively marketed as a degradable conventional plastic. It is licensed by EPI, and used in many applications: mulch films, PE bubble wraps and bags, non-food contact films, compostable bags, and shopping bags. The start of degradation ranges from several weeks to several years, but the products are intended to degrade within 20-36 months, when disposed in
“appropriate” environments (Ammala et al. 2011). In laboratory testing, loss of properties (mechanical strength, brittleness, chain shortening and compound oxidation) occurs within weeks at 71°C (Scott and Wiles 2006). After exposure to heat, molds and fungus can grow on TDPA, causing surface pitting (Bonhomme et al. 2003). However, TDPA bag strips immersed in 0.6 m of seawater lost mass but did not lose structural integrity after 40 weeks of exposure, although starch bag strips fell apart after 24 weeks (O’Brine and Thompson 2010). No degradation was observed after 32 days inclusion in an anaerobic flask with sewage sludge; methane gas generation was no different from a control (Mohee et al. 2008). Degradation begins more quickly under dry and warm conditions (Chiellini et al. 2006), and is faster and more complete in soil than in compost (Ammala et al. 2011). After 18 months in soil, heat-treated samples were 60% mineralized, and degradation, as measured by CO₂ evolution, was found to be continuing (Chiellini et al. 2003). After 70 weeks of soil burial no recognizable soil fragments could be recovered, a rate that was slightly slower but similar to how cellulose decomposed (Ammala et al. 2011). A landfill cover film made from polyethylene and TDPA was buried for three months and then found to no longer be intact, and another film, after 14 months exposure, was reduced to average molecular weights of approximately four kDa (Swift and Wiles 2004). For compost, however, a 12-day artificial compost exposure resulted in no measurable changes to three different formulations (Day et al. 1997). Exposure of three other film formulations to 45 days of MSW composting resulted in weight losses but no change in the plastics’ appearance (Agamathu and Faizura 2005). Exposure to 72 days of MSW compost showed no degradation of the material, although some CO₂ generation was measured (Mohee et al. 2008). In compost at 55°C, 25% of the carbon was respired after 14 months (Ammala et al. 2011). Testing in a municipal composting plant found the product was biodegradable: that is, the product was
reduced to “particulate and partially biodegraded plastics” (Scott and Wiles 2006), which, since
the product passed toxicity tests and EPI rejects the compostable standards as unreasonably
demanding, was deemed sufficient (Billingham et al., 2000).

Reverte is added to polypropylene and polyethylene to make retail bags, garbage bags,
food containers and utensils, and trays, and also to polyethylene terephthalate (PET) for use in
beverage containers. Reverte plastics contain about 0.5% starch as well as prooxidant additives.
These compounds add carbonyls on exposure to UV and are susceptible to microbial
degradation, as tested by in-house experiments, and also can be colonized by fungi. Up to 60%
of carbon was mineralized after two years of column compost testing (Ammala et al. 2011).

BioSmart plastics can be added to PE and PP like Reverte, but appear to have their use
limited to PVC shrink wraps. Its iron additive makes most products yellow-brown or darker
brown, although the company has worked to minimize these color effects. Additives prevent
degradation from starting for up to two months of UV exposure. Compost conditions (defined as
exposure to UV followed by 70°C heat) resulted in greater brittleness (Ammala et al. 2011).

Addiflex makes degradable PE food packaging, food service goods, retail and garbage
bags, and drop cloths. Oven exposure (80°C for eight days) resulted in greater brittleness.
Inclusion of film products in feedstock at a green waste composting facility showed the plastics
became brittle after two weeks, lost integrity after six weeks, and only 20% were detectable after
12 weeks (Ammala et al. 2011).

Symphony Environmental makes plastic additives that are used in plastic products for
companies including Nescafe, Pizza Hut, KFC and Walmart. These products do not degrade
under anaerobic conditions (Ammala et al. 2011).
Plastor and Plastigone products are used in mulch films. They are intended to begin degrading under UV exposure (Ammala et al. 2011). No independent studies seem to have been conducted regarding this or other degradation potentials.

ECO plastics are used for six-pack rings. They are intended to degrade due to UV exposure, and have been shown to increase carbonyl groups after exposure to sunlight (but not when under glass), becoming brittle after six weeks exposure on a rooftop or in seawater. However, no test of microbial decay following embrittlement has been conducted (Ammala et al. 2011). Early compostable bags did not score well under testing (Farrell et al. 2001).

Ecolyte plastics are used in mulch films and packaging. They are designed to be sensitive to UV, although increasing the additives to make degradation more probable reduces properties as a polyethylene. It has been suggested they react more strongly to UV than ECO brand-type plastics. No demonstration of degradability by microorganisms has been made (Ammala et al. 2011).

Biobatch is a developing product that is intended to be added to polyolefins to result in degradation. It contains chemicals that are said to attract microorganisms, and also will use sugars and other microbial substrates to make the plastic initially palatable. No field testing was reported (Ammala et al. 2011).

Polyvinyl alcohol has unusual properties for a sealable plastic. It is water soluble, solvent resistant, strong, resistant to oil and greases, and reportedly degrades readily in water and/or common microorganisms. It is used in laundry applications (Davis 2003). It is reported that degradation will be completed in 30 days (ExcelPlas Australia et al. 2004).

Certain consumer products are labeled as degradable without offering any overt or independent certifications as to their actual performance, such as the organizational certifications
discussed above. We have noted that at sites where there are expectations for sound environmental sensibilities (e.g., farmers’ markets and college campus retail locations), it is common to receive goods in plastic bags that are stamped “degradable.” At the Huntington, NY, farmers’ markets, buyers receive opaque film bags that are simply labeled “degradable plastic,” with no other explanation. We have not been able to trace the manufacturer. At the Stony Brook University (NY) Wolfmart, a white film plastic bag is used, labeled “Oxo-Biodegradable™ Bag.” Below that label was an explanation:

“[t]he plastic used in this bag will convert to water, carbon dioxide and biomass in the presence of soil, moisture and oxygen. Like a fallen leaf, it will disappear over time.”

There was a further label of “epi totally degradable plastic additives,” with the dot in the “i” replaced with a stylized flower face. EPI is the licenser of TDPA. However, as related above, there is little independent evidence that TDPA-treated plastic bags will “disappear” in a short period of time.

Several government-sponsored reports on degradable plastics (CSU Chico 2007, ExcelPlas Australia et al. 2004) found little evidence in either scientific literature or through independent testing that “oxo-degradable” materials biodegrade. Scott has argued that the definitions applied to degradable plastics are unfair, since many organic polymers do not degrade in the environment in short time frames; he is partial to comparing rubber and wood to oxidizable polyolefins, and claims that the plastic polymers lose properties at similar or faster rates than the natural polymers (Scott 2000; Scott and Wiles 2001; Wiles and Scott 2006). However, this means that the oxo-degradable plastics remain in the environment for years, so that consumer expectations do match their experiences.

Tables 1 and 2 summarize some findings on compostable and degradable plastics.
Table 1. Compostable plastics

<table>
<thead>
<tr>
<th>Plastic</th>
<th>Certified</th>
<th>Independent Testing</th>
<th>Manufacturer Claims of Degradability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starch-based</td>
<td>Generally</td>
<td>Much</td>
<td>Yes</td>
</tr>
<tr>
<td>PLA</td>
<td>Generally</td>
<td>Much</td>
<td>Yes</td>
</tr>
<tr>
<td>PHA</td>
<td>Generally</td>
<td>Much</td>
<td>Yes</td>
</tr>
<tr>
<td>AAC</td>
<td>Some</td>
<td>A little</td>
<td>Yes</td>
</tr>
<tr>
<td>PLC</td>
<td>Some</td>
<td>A little</td>
<td>Yes</td>
</tr>
<tr>
<td>Starch-inserted conventional</td>
<td>Generally not</td>
<td>Some</td>
<td>Yes</td>
</tr>
<tr>
<td>Oxo-degradable</td>
<td>No</td>
<td>No*</td>
<td>Yes**</td>
</tr>
</tbody>
</table>

* negative results ** often offer alternative definition of compostable

Table 2. Degradable plastics

<table>
<thead>
<tr>
<th>Plastic</th>
<th>Degradability – Independent Testing</th>
<th>Degradability – Manufacturer Claims</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starch-based</td>
<td>Completely</td>
<td>Completely</td>
</tr>
<tr>
<td>PLA</td>
<td>Completely</td>
<td>Completely</td>
</tr>
<tr>
<td>PHA</td>
<td>Completely</td>
<td>Completely</td>
</tr>
<tr>
<td>AAC</td>
<td>Completely*</td>
<td>Completely</td>
</tr>
<tr>
<td>PLC</td>
<td>Completely</td>
<td>Completely</td>
</tr>
<tr>
<td>Starch-inserted conventional</td>
<td>Mixed results</td>
<td>Completely</td>
</tr>
<tr>
<td>UV-initiated</td>
<td>Mostly not</td>
<td>Completely</td>
</tr>
<tr>
<td>Oxo-degradable</td>
<td>Not</td>
<td>Completely**</td>
</tr>
</tbody>
</table>

* not shown directly ** often offer alternative definition of degradable
5. Compatibility of Degradable Plastics with Current Waste Management Processes

5.1 Composting

Four kinds of wastes are composted in the US: sewage sludges, yard wastes, food wastes, and MSW (Epstein 2001). The latter two are collected curbside. MSW is always contained, and most yard wastes are too in suburban and urban environments. Paper and plastic bags are often used for these purposes, even when reusable garbage cans are set out. Specialized paper bags for yard wastes are expensive, although they are degradable. Conventional plastic bags cause output contamination (Epstein 2001).

Degradable plastics are primarily intended to address composting contamination (and litter issues). Compostable plastics require specific levels of moisture and oxygen for initial reactions to occur to make the polymers consumable by bacteria (Song et al. 2009). These conditions are usually only found in larger, industrial-commercial facilities, where materials are regularly turned, and usually have been pre-processed (often shredded) (Kale et al. 2007). Initiation of degradation either requires hydrolyzation (for PLAs) or reactions with enzymes from microorganisms (PHAs), making large polymers smaller and simpler. These smaller molecules can pass through semi-permeable cell membranes to be used as energy sources, nominally creating wastes of water and CO$_2$. In composting, there is an intention to produce some quantum of residual organic matter (humus), at least some of which is biomass associated with the microbial and macrobiota consumers (Shah et al. 2008): some portion of compost organic matter is expected to be indigestible (Scott 2000; Scott and Wiles 2001). Thus, performance standards for degradable (compostable) plastics do not require all polymers to be consumed, so that absolutely no plastic remains. In the UK, plastics must be 90% consumed in laboratory testing (the test is assumed to have 10% variability on average); in other jurisdictions,
the typical requirement is to “degrade to the degree that compost inputs do” (Song et al. 2009). Standards often add an element of toxicity testing (CSU Chico 2007, Wiles and Scott 2006), minimizing the potential for the compost product to cause harm to plants, animals and humans (Tosin et al. 1998).

Compostable plastics under standard, large-scale composting practices have been found to degrade well, with different kinds of substrates, such as yard waste, manure, and food waste (Kale et al. 2007), or using different technologies, such as turned windrow or in-vessel (CSU Chico 2007). These results have led to endorsement of their wider use. For instance, San Francisco encourages the use of compostable liner bags in its mandatory curbside organic waste separation program. The bags are intended to be compatible with the City’s compost process and provide users with acceptable container sanitation (Chester et al. 2008; Kale et al. 2007). Mulch films are another area where compostable plastics are perceived as technological advances, as dirt adhesions to the films make them difficult to recycle (Scheirs 1998) but may actually enhance compostability.

However, reports of failure to perform by compostable-labeled plastics in at-home composting environments are common. Inadequate temperatures in these smaller piles, so that the key hydrolysis reaction for PLAs is not initiated, are thought to be the reason for much of the poor results (Song et al. 2009; Farrington et al. 2005). This has reignited controversies associated with earlier degradable plastic products, due to the mismatch between producer claims and consumer experiences. The Sustainable Packaging Alliance (Australia) (2009) stated that the use of compostable bags is limited because jurisdictions need to ensure formulations are compatible with the system accepting the waste (and bags).
Composting plastics minimizes the amount of waste which goes to landfills. Reducing the landfilling of waste has been a major public policy initiative for decades (Sidique et al. 2010; Loughlin and Barlaz 2006), but more than half of all US solid waste is currently landfilled (USEPA 2010; van Haaren et al. 2010). Yard and food waste, according to sampling across the US, constitute at least 10% (and sometimes much more) of disposed wastes, even in crowded cities or rural areas where yard waste is not disposed (Table 3). USEPA (2010) found food wastes to be 20.3% and yard wastes 8.3% of disposed wastes in 2009. Thus, those seeking to increase waste recovery see organic wastes as a great opportunity for additional composting (NYSDEC 2010). Contamination of yard wastes with plastic bags is a major operational inconvenience, and institutional food waste composting requires removal of unwanted plastic cutlery and the like (see Figure 1). Compostable plastics are perceived as means to address these issues.

Table 3. Percent yard and food waste in disposed wastes (sampling results)

<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>Yard waste</th>
<th>Food waste</th>
<th>Total</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vermont†</td>
<td>2001</td>
<td>0.7</td>
<td>21.3</td>
<td>22.0</td>
<td>DSM Environmental Services 2002</td>
</tr>
<tr>
<td>Georgia‡</td>
<td>2003-2004</td>
<td>7.6</td>
<td>16.4</td>
<td>24.0</td>
<td>RW Beck 2005</td>
</tr>
<tr>
<td>Iowa‡</td>
<td>2005</td>
<td>1.6</td>
<td>10.6</td>
<td>12.2</td>
<td>RW Beck 2006a</td>
</tr>
<tr>
<td>California</td>
<td>2008</td>
<td>3.8</td>
<td>15.5</td>
<td>20.3</td>
<td>Cascadia Consulting Group 2009</td>
</tr>
<tr>
<td>New York†</td>
<td>2004-2005</td>
<td>9.9</td>
<td>15.9</td>
<td>24.9</td>
<td>RW Beck 2006b</td>
</tr>
<tr>
<td>Chicago‡</td>
<td>2007</td>
<td>1.2†</td>
<td>20.7</td>
<td>21.9</td>
<td>CDM 2010</td>
</tr>
<tr>
<td>Phoenix‡</td>
<td>2003</td>
<td>28.1†</td>
<td>16.8</td>
<td>44.9</td>
<td>Cascadia Consulting Group et al. 2003</td>
</tr>
</tbody>
</table>

† residential wastes; ‡ residential and commercial wastes; † compostable yard waste only; † single family residential wastes only
However, there are concerns that composting plastics invalidates the resulting product for organic certification and subsequent use on organic farms (Sullivan 2011). Tentative organic certification rules for degradable plastics in organic compost may require specification of the source of the feedstock for the plastic, with petroleum-based plastics not qualifying as organic, but plant-based degradable plastics meeting this organic standard (Fernandez-Salvador 2012), a process which may be complicated to implement. A primary purpose of degradable plastics is to support greater composting use; however, it is not clear that these degradable plastics will win
widespread acceptance if the resulting compost product may not be considered organic, and/or there continue to be widespread failures in at-home usage.

5.2 Recycling

Recycling is the primary method used to minimize waste in landfills and it is perceived to be the most preferable means of managing plastics (e.g., Brandrup 2003; Lazarveric et al. 2010). However, many resins are difficult to recycle (Kuswanti et al. 2003); one cause of problems is certain resins are intolerable contaminants for other resins (Goodship 2007); PVC is often singled out in this regard (Belliveau and Lester 2004; Park et al. 2007). The high volume-weight ratios for some plastics, especially blown polystyrenes, makes collection and transport of some products very difficult and/or expensive (Goodship 2007). Sorting plastics to general resin categories can be challenging (Kuswanti et al. 2003); many plastics products look similar but are of different compositions (Park et al. 2007), and some plastic wastes are small and difficult to handle (Richard et al. 2011; Kinoshita et al. 2006). Different polymers can be similar in density, so that float sortation is not efficient (polypropylene and HDPE are examples) (Scheirs 1998). Styrofoam peanuts are notoriously difficult to handle, due to extremely low density and static cling. Contaminants adhering to plastics can cause processing issues for certain means of materials recovery (Lazarevic et al. 2010), and some chemicals attached to plastic products, such as adhesives, are difficult to manage and cause production quality control issues (Scheirs 1998).

Generally, in order for plastics to be recycled, well-characterized, single material product streams need to be created (Goodship 2007). Thermoset plastics, which are mostly rigid, structural forms (Gruenwald 1993), are difficult to recycle because the thermosetting process changes the plastics’ structure, so that it is not possible to recover the underlying poly/monomer through most processes (Pickering 2006). Recycling of thermoplastics requires remelting them;
early quality issues with secondary products from recycling, such as plastic lumber, resulted from differences in melt temperatures with different polymers. Remelting thermoplastics leads to loss of polymerization and thus to some deterioration of materials properties so that even collections of some single polymers are not indefinitely recyclable (Goodship 2007). For instance, intrinsic viscosity of PET decreases with each re-melt. For a 50% recycled content PET bottle, due to accumulating extrusion histories, one calculation was there will be a decrease in intrinsic viscosity of the resulting product of over a third. Technology adaptations and additives exist that can minimize or eliminate the reductions in polymer strength. HDPE tends not to degrade through recycling, although tinting of resins from included colored caps causes reductions in the utility of recycled products, and “black speck” inclusion (resulting from flakes that have too long residence time in an extruder) is another aesthetic problem. High milk container content reduces crack resistance, as well, which limits recycled content in many applications. For PVC, as little as 1% contamination levels can cause problems in the reformation process (Scheirs 1998).

Degradable versions of products differ from conventional plastics in either base polymers or additive mixtures; this means that the increase in input heterogeneity will reduce the quality of the recovered plastic. A test mix of 5-10% of a variety of degradable and compostable plastics with HDPE and LDPE resulted in decreases in mechanical and aesthetic properties (CSU Chico 2007). Reports from Australia suggest that recyclers there do not want to accept degradable plastics for two reasons. One, the resulting products exhibit loss of plastic properties. Secondly, there are concerns regarding potential later degradation of these end products (ExcelPlas Australia et al. 2004, The Sustainable Packaging Alliance 2009). Clearly, degradation of the resulting recyclate would not be desired. This issue would be magnified if segregated
accumulations of degradable plastics were to be made, since any partial degradation of feedstock would make the resulting recycled product less suitable for reuse (Goodship 2007; Song et al. 2009). In addition, if degradable plastics constitute appreciable amounts of the plastics recyclables stream, there is concern regarding the stability of long-life (construction) and medium life (outdoor furniture) applications (Thomas et al. 2012). However, the current consensus appears to be that degradable plastics can be considered to be recyclable, as they constitute only a very small part of overall feedstock, not enough to make a measurable impact given other concerns in recycling plastics (Al-Malaiki et al. 1995; Song et al. 2009).

5.3 Waste-to-Energy Incineration

The processes in waste-to-energy (WTE) incineration would not be affected by whether input plastic is degradable or not. However, the use of bio-based resins would reduce fossil CO₂ emissions. Current estimates are 56% of all energy resulting from WTE incineration comes from biogenic organic MSW, and so combustion of MSW produces energy that is at least half-derived in a way that does not increase the amount of CO₂ in the biosphere (Energy Information Agency 2007). The amount of fossil carbon in MSW (and its percentage of the energy content) is increasing with growing use of petroleum-stock plastics, however. WTE incineration has been identified as a means of producing electricity with fewer climate change impacts than the standard US grid mix of generation sources (Bahor et al. 2009), so more bioplastics use would increase the environmental benefits of this process. Still, producing degradable plastics with the aim of improving the performance of WTE incinerators is not especially efficient, although it could be an unintended, pleasant side effect. Many degradable plastics are made from renewable feedstocks (Suriyamongkol et al. 2007); the production of conventional plastics uses 4% of the world’s annual petroleum production (Andrady and Neal 2009). Therefore, increasing the market
share of degradable plastics would slightly reduce demands on diminishing petrochemical reserves (Suriyamongkol et al. 2007), and, if offsetting uses for the petroleum were not found, could somewhat reduce the potential for global climate change due to CO₂ emissions (Dornburg et al. 2004; Gross and Kalra 2002).

**5.4 Landfilling**

Most waste in the US is disposed in landfills (USEPA 2010, van Haaren et al. 2010). Landfills are ranked lowest on the USEPA hierarchy because of their potential for environmental impacts. The primary impacts from landfills are landfill leachate generation (which threatens water quality) and gas generation (escaping methane can cause local explosion dangers and is a potent greenhouse gas). Landfill mesocosm and other laboratory experimental work (e.g., Pohland et al. 1993; Eleazar et al. 1997) support the notion that biological degradation processes are the primary control on leachate quality (Christensen and Kjeldsen 1989). This suggests degradation of organic matter is an important process in landfills. In a Swedish test cell, ~50% of paper, animal, and vegetable matter degraded over 20 years (Flyhammar et al. 1998), and samples from several landfills indicated that degradation of more labile organic matter was common (Bookter and Ham 1982). However, some other experimental work and excavations of landfills found that most organic wastes will not degrade even after decades. Wall and Zeiss (1995) estimated 20% of organic wastes would degrade over a landfill lifetime (degradation was estimated to be log-linear with time), and Rathje (as reported in Rathje and Miller 2001) found only 2-5% of an Arizona’s landfill contents degraded after 15 years. Bozkurt et al. (1999) modeled landfill processes, and suggested most organic matter may not be affected by landfill residence except on time scales of centuries or more.
Gas generation is not always perceived as a negative feature of landfilling. If the gas can be efficiently captured with little losses to the atmosphere, then it represents an environmental benefit if it can be used to generate electricity. The benefits accrue because landfill methane is produced from non-fossil carbon, and so is classified as “green” energy (Jaramillo and Matthews 2005). However, methane is more potent a greenhouse gas than CO₂, so depending on the portion of methane that escapes collection, gains may or may not be realized by displacing fossil fuels at conventional electricity sources. One estimate is that between 35% and 90% of methane can be captured, depending on the landfill cover system (Spokas et al. 2006). If there is little to no fugitive gas from a standard landfill gas to energy system, and if degradable plastics were consumed by microbes in landfills, then the use of degradable plastics would increase potential reductions in overall greenhouse gas emissions associated with the technology (Levis and Barlaz 2011). Wiles and Scott (2006) and ExcelPlas Australia et al. (2004) hypothesize that loss of mechanical strength and other degradation of plastic bags could enhance gas production, on the theory that intact plastic bags prevent access by microorganisms to their contents and so either prevent or slow the degradation of labile carbon in landfills.

Replacing recalcitrant plastics with plastics that have greater potential to degrade may result in greater degradation of the plastics themselves – if the degradable plastics encounter conditions that result in depolymerization. Burial of UV-sensitive plastics is not likely to result in any early plastics decay. Plastics where degradation is initiated by higher temperatures are more likely to start decomposing in most landfills. For instance, landfill cover film made of polyethylene and TDPA lost integrity in one three month trial, and average molecular weight was reduced to less than five kDa after 14 months at another site (Swift and Wiles 2004). Most degradable plastics that are “compostable” generally require moisture and oxygen for the process
to proceed very far, however. Moisture may or may not be available in particular landfills or areas in landfills, but landfills generally are known to be lacking in oxygen. No studies of compostable plastics in landfill environments were located (per ExcelPlas Australia et al. 2004), although some starch-based plastics have degraded in simulated anaerobic digesters (CSU Chico 2007). The first generation of degradable plastics, which did not meet compostable standards, showed no notable degradation in landfills (Breslin and Swanson 1993). Although Swift and Wiles (2004) suggest anaerobic decay of degradable plastics will occur (albeit slowly), it seems more likely that degradable plastics will not behave very differently from petroleum-based plastics in most landfills.

Some have identified the lack of degradation of organic material in a landfill as a benefit. This is because no decay of organic matter represents a sequestration of carbon (Staley and Barlaz 2009), especially if retarded for centuries or more (Bozkurt 1999). In this view, however, even potentially degradable organic compounds reduce environmental benefits.

Thus degradable plastics in landfills offer the following potential effects:

1) decay and release of more methane – which is a benefit if enough gas is captured and used as an alternative energy source, but otherwise causes more environmental problems

2) decay and production of higher strength leachate, which poses an environmental problem

3) sequestration of carbon, which reduces overall climate change impacts and so is an environmental benefit. If the degradable plastics are biobased, this benefit would be greater than burying petroleum-based plastics, as petroleum-based plastic sequestration represents prevention of the release of old carbon, while
The sequestration of biobased plastics represents a drawdown in current stocks of circulating CO₂.

Since it seems most likely that degradable plastics will not decay readily in landfills, use of these products likely would lead to a small environmental benefit due to enhanced sequestration effects.

5.5 Litter

Their persistence when inappropriately strewn into the environment makes plastics the poster-child for litter issues (Rochman et al. 2013) (Figure 2). It has been argued that if plastics were to be degradable, even at timescales of several years, it would reduce the impact of litter tremendously (Guillet et al. 1995). It has been asserted that most compostable plastics do not degrade very well outside of compost piles (Song et al. 2009). Scott argues that this highlights the value of UV-sensitive degradables, as they will be affected by the environment if left in the open, as most litter is (Scott 2000; Scott and Wiles 2001; Wiles and Scott 2006). Certainly UV sensitivity would appear to be a better attribute for plastics than compostability if persistence of litter is the issue at hand.

One test of PHB materials found that the coated cups would either entirely degrade or almost entirely degrade within a year in laboratory tests designed to simulate key attributes of marine settings. Greater degradation occurred in bacteria-inoculated salt water when additional nutrients and sediments were added; in the absence of additional nutrients, even readily labile materials often did not degrade entirely, and neither did the PHB-coated cups. PHB films had approximately similar results (Ratto et al. 2001).
UV-sensitive plastics require exposure to sufficient radiation for degradability to be initiated. If plastics accumulate in the open or float on the water, then they are likely to receive significant UV exposure. However, certain plastics have sufficient density (or retain not enough air) to sink below the ocean’s surface, and these plastics may not receive enough UV energy to cause initiation of decay. In that case, since they lack any means to initiate decomposition, they are functionally the same as conventional plastics. O’Brine and Thompson (2010) found that bag strips set in 0.6 m of water were fouled by macro-organisms and algae after eight weeks, which also would impede UV exposure; perhaps consequentially, the UV-triggered degradable bag formulation they tested was still cohesive after 40 weeks of exposure, although it had lost some mass. However, that study found a starch-based compostable plastic degraded enough to lose its integrity before fouling occurred. A marine exposure test, over 14 and 21 day test periods, of a
range of compostable, UV-sensitive, and oxidative degradable bags and materials by CSU Chico (2007) found that UV-sensitive six-pack rings became brittle, and the PHA-based plastic lost 36-60% of its mass, but none of the other plastics had any detectable degradation.

In the degradation of plastic polymers, no matter the mechanism or process, a point can be reached where “fragments” are created. At this stage, either these residues prove to be recalcitrant (on meaningful time scales) or the fragments decompose further. With further decomposition, either the compounds become incorporated into biomass (in a sense, functionally reduced to CO₂) or a residue will be created. The recalcitrant residues need to be characterized, both chemically and in terms of their potential environmental effects (Karlsson and Albertsson 1995; Swift 1995), although this is rarely done. Fragmentation of plastics eliminates the visual blight of plastic litter and would seem likely to reduce ingestion of plastic by organisms that search for food using visual clues (ExcelPlas Australia et al. 2004). However, microlitter, with its greater surface area, serves as ready sorption sites for organic pollutants, and can be consumed by filter-feeding organisms in the ocean or earthworms on land (Thomas et al. 2012; Rochman et al. 2013). Therefore, plastics that only partially degrade still represent substantial environmental problems if they become litter (Breslin and Swanson 1993).

The government of Australia mandated that all “bait bags” be made of degradable plastics to address one marine litter issue. A particular formulation by Mater-Bi has been the choice of manufacturers (it is a starch-conventional plastic mix). Testing appears to show 10% weight loss over three weeks seawater exposure, and an estimated six month degradation time in total. Tests have been conducted to mimic the effect of turtle digestive juice on the bags (ExcelPlas Australia et al. 2004) (but results were not reported).
Table 4 summarizes potential impacts on current waste management practices from the use of compostable and degradable plastics.

Table 4. Impacts of degradable and compostable plastics on current waste management practices

<table>
<thead>
<tr>
<th>Waste Management Practice</th>
<th>Compostable Plastics</th>
<th>Degradable Plastics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composting</td>
<td>Reduce-eliminate contamination at industrial sites; cause contamination of end product at small and backyard sites</td>
<td>Cause contamination of end product</td>
</tr>
<tr>
<td>Recycling</td>
<td>Increase resin complexity, cause recyclate quality issues</td>
<td>Increase resin complexity, cause recyclate quality issues</td>
</tr>
<tr>
<td>WTE Incineration</td>
<td>No impact</td>
<td>No impact</td>
</tr>
<tr>
<td>Landfilling</td>
<td>No apparent impact beyond some C sequestration</td>
<td>May have slight beneficial effects if enhanced gas generation is sought; potential C sequestration</td>
</tr>
<tr>
<td>Litter</td>
<td>Starch-based resins will degrade; PHB may degrade; others may not</td>
<td>Visible effects may be decreased (for UV-sensitive plastics); otherwise, no enhanced degradation</td>
</tr>
</tbody>
</table>
6. Degradable Plastics and Effects on Proposed Solid Waste Management Technologies and Strategies

6.1 Expanded Recycling

Most US municipal recyclables collection programs were established in the 1980s and 1990s, and can now be considered to be mature. National evaluations of recycling have generally shown relatively flat rates over the first decade of the new millennium (USEPA 2010; van Haaren et al. 2010). Still, expectations are (and associated plans call for) increased recovery rates over time (see NYSDEC 2010, for instance).

One proposed mechanism to increase recycling rates is to inject economic factors into collection processes, using an idea known as “Pay as You Throw” (PAYT). PAYT means that waste generators pay variable amounts depending on waste management practices, with separated wastes for recycling generally being free and those requiring disposal being charged either by weight or volume. Although the impact of PAYT is difficult to isolate from other programmatic changes, one analysis of multiple locations that attempted to control for extraneous factors suggested as much as 5% more of the waste stream will be diverted to recycling (Skumatz 2008). Plastics, by best available estimates, are becoming a larger proportion of recyclable products, replacing glass, metal, and paper alternatives (USEPA 2010), so that the recovery of plastics is likely to be a more substantial component of recycling statistics over time. As discussed above, degradable plastics have the potential to reduce the recyclability of plastics, especially if their share of the plastics market increases. Therefore, increasing use of degradable plastics may hinder efforts to increase conventional recycling rates.
6.2 Expanded Organics Recovery

Organic wastes such as food wastes are often considered to be the best target to make appreciable increases in solid waste recovery rates (USEPA 1999; Cuellar et al. 2010; NYSDEC 2010). Although food reuse and waste reduction programs have received some attention, the primary recovery of food wastes (and related organic matter such as soiled paper) is to be through either composting or anaerobic digestion (enclosed decomposition of matter by organisms producing gases such as methane and CO₂, and a solid organic residue).

Key to the success of either process is the capture of food waste from the waste stream, with minimal inclusion of materials that are not degradable by organisms. Processes where organic wastes are produced in large quantities in a controlled fashion – food processing plants, industrial kitchens, institutions (such as prisons and offices with on-site cafeterias), even supermarkets – seem to generate waste streams with less contamination potential than residential or front-of-the-restaurant collection programs, where differing perceptions of proper participation cause quality control issues. Degradable plastics are generally identified as an important means to reduce contamination effects, although the degradable plastic in the wastes needs to be matched with the degradation process to be utilized (Mohee et al. 2008). Compostable plastics, if they require oxic conditions to complete degradation, may not be consumed by anaerobic organisms in digesters, for instance. So, for instance, PHA plastic underwent 38% degradation under anaerobic conditions in a 50:50 mix with food waste, but PLA only had minor degradation (6%), as did other formulations that were tested (such as UV-sensitive or oxidative degradable plastics) (CSU Chico 2007).

Along with bags and agricultural films, plastic utensils and packaging that currently contaminate compostable waste streams are being targeted by compostable plastics.
manufacturers as primary market opportunities. Organizations that want to appear to be progressive in waste management practices are adopting compostable plastic materials for use although they do not currently have a food waste or other organic waste diversion program (such as at our home institution). However, incomplete market penetration may result in, say, compostable plastics being disposed instead of separated for composting, or conventional plastics included in the compostable waste stream, due to consumer confusion.

Compost sites often create objectionable odors (Buckner, 2002; Goldstein, 2002; Gage, 2003, Goldstein, 2007). This has made it difficult to operate the cheapest kind of compost site, one with outdoor composting, in regions where the most wastes are generated. Anaerobic digestion, which requires enclosed degradation with gas capture, and can generate electricity from these gases, may be the preferred future technology. Anaerobic digestion is a proven technology for organic wastes generally, and has had commercial success in treating source-separated organic wastes from the solid waste stream. Anaerobic digestion requires that waste compounds be amenable to decomposition by well-characterized bacteria (Demirbas et al. 2011). As was discussed above in connection with landfills, it is not clear that compostable plastics can provide the proper substrates for decomposition under anaerobic conditions. Mater-Bi degradable plastic degraded about half as well as cellulose over a 32 day simulated digester exposure (Mohee et al. 2008), which is either a hopeful or poor result, depending on perspective. If anaerobic digestion is to be the preferred technology for managing organic portions of solid waste, degradable plastics may not be appropriate to include in the feedstock, as they appear likely to add to residues.

Contaminants are best removed prior to composting or digestion, as pre-processing to increase efficiency often includes grinding or other processes that reduce particle sizes, which
results in residues that are difficult to identify and separate because they are so small. If conventional and degradable plastics are not easily distinguishable, then incomplete market penetration will mean that it is better to exclude all plastics (if possible) from feedstocks. This may be possible: at an Italian plant, all degradable plastics were removed in pre-processing through a technology that targeted (conventional) plastics (Garaffa and Yepsen 2012). In Europe, where one element of organic waste processing is to produce a largely inert material to meet landfilling requirements (Demirbas et al. 2011), the creation of a not-marketable solid residue is not an impediment to use of this technology, and the poor degradability of degradable (or conventional) plastic formulations under anaerobic conditions would not seem to be an issue. If the digestate or residues are to have some future commercial use, as is often the case in the US, then allowing materials that tend to be recalcitrant into processes is not beneficial.

6.3 Innovative Energy Recovery

Over the past several decades various technologies have been considered as alternatives to mass-burn incineration, primarily because of its general inefficiencies in energy recovery (Murphy and McKeogh 2004). Pyrolysis (the degradation of organic molecules under low-no oxygen conditions) (Demirbas and Balat 2007) and gasification (conversion of organic solids to gases under high heat and pressure conditions) (Arena 2012) have been receiving more attention in recent years, as underlying technologies have been refined and the potential for improved performance over incineration has been appreciated. A third alternative technology, plasma arc gasification, while potentially netting more energy with fewer residuals (Mountouris et al. 2006), seems further from commercial application.

Whether plastic feedstocks are degradable or not should be meaningless in the context of these technologies. They degrade molecular bonds through the application of energy, and there is
no biological component to be considered. Source separated plastics are currently successfully processed through these technologies (Williams and Williams 1997, Panda et al. 2010); the success or failure of these more delicate processes when applied to general municipal solid waste will not be affected by minor differences in plastics chemistry, but rather by more global issues of solids-residues quality and contaminants in fuel stocks.

6.4 Bioreactor Landfills

Bioreactors landfills are operated, in contravention of standard landfilling practices, to enhance degradation processes. This is usually accomplished by increasing the liquids content of the fill, primarily by not removing leachates and instead re-circulating them through the wastes. Enhanced degradation increases the generation of methane, which means there is greater recovery of the inherent energy in the wastes (the necessary assumption is there will be effective methane capture and the subsequent production of electricity or liquid fuels). Enhanced degradation also implies faster settling of wastes, allowing for airspace to be (in a sense) reused or resold. Quicker, more complete degradation of wastes may also mean that a site is determined to have “stabilized” sooner, reducing long-term monitoring costs and responsibilities (Warith 2002).

Degradable plastics that depend on exposure to UV radiation will not degrade faster than conventional plastics under bioreactor landfill conditions. Plastics affected by higher temperatures could have degradation processes initiated by the elevated temperatures found in bioreactors (akin to composting sites), but compostable plastics require moisture and oxygen. Bioreactor landfills are intended to be very moist, but not aerobic. Therefore, degradable plastics should behave in a bioreactor as they do in a standard landfill: most probably not degrade any
more quickly than conventional plastics, negating the reasons for selecting them (but causing no negative consequences, either).

### 6.5 Extended Producer Responsibility

“Extended producer responsibility” (EPR) describes policies which legislate incentives for manufacturers to incorporate environmental considerations in the design of products, and shift physical and economic post-consumer responsibility to the producer or seller of the product (Fishbein 1998; Lifset 1993; Nash and Bosso 2013; OECD undated). EPR programs intend to create links between product design and end-of-life management (Lewis 2005; Hickle 2007; Quinn and Sinclair 2006; Lifset and Lindhqvist 2008). EPR generally requires that the specific users of products bear financial responsibility for end-of-life management, usually by explicitly incorporating end-of-life costs into the product’s price, which could create consumer cost preferences (Lifset 1993; Palmer and Walls 1999). This, and the fostering of reuse and recyclability through performance standards, are intended to create an impetus for Design-for-the-Environment (DfE) (Lifset 1993; Lifset and Lindhqvist 2008). DfE broadly includes considering the environmental impact of input material resources and end of life effects in the design of the product, moving beyond performance/materials availability and cost bounds that are central to traditional design. Notionally, DfE increases the use of recycled products and reuse, minimizes environmental effects from resource extraction and production, and promotes more sustainable materials management (Lifset 1993; Lifset and Lindhqvist 2008). When DfE is extended to post-consumer arenas, it should encourage redesign of products to minimize end-of-life environmental impacts and increase post-consumer value (Quinn and Sinclair 2006; Lindhqvist and Lifset 1999). EPR makes it essential that product designers understand the
environmental, social, or health impacts associated with the product life cycles (Veleva 2008; Nash and Bosso 2013).

Not all EPR initiatives share equally in all of these rationales. To this end, compostable and degradable plastics fit many but not all of EPR criteria. Compostable plastics from biomass feedstock seem to more sustainable, in that they are made from renewable materials and are to be managed through an environmentally favored waste management method. Thus, they fit with some DfE concepts, as clearly their design involves concern about their impact on the environment. Another important element of EPR is to simulate technological change and innovation toward an environmental benefit (Tojo 2004), as has been the case with degradable plastics. However, EPR economic concepts do not fit as well: manufacturers of degradable plastics have no explicit involvement in their end-of-life management, especially in terms of financial support; and these products are much more expensive for consumers, sending a negative price signal. Toffel (2003) noted EPR imposes various combinations of economic, physical, informative, or legal responsibilities upon manufacturers. However, degradable plastics manufacturers assume only the informative burden (depending upon the perception of where the burden of additional costs associated with creating the degradable products falls). Degradable manufacturers do not explicitly pay for any end-of-life costs, unless the extra manufacturing costs are seen as implicitly accounting for some end-of-life expenses.

Ultimately, the only mechanism to increase compostable products use will be through more extensive use of composting facilities which accept them (Gross and Kalra 2002). This may only be possible through governmental mandates to build such facilities. Until infrastructure is available, conversion from conventional to compostable plastics will have no environmental
benefit if most waste continues to be landfilled. Thus, the DfE purpose of compostable plastics is difficult to achieve under current and foreseeable conditions.

The second aspect spurring EPR development is usually less explicitly discussed. Targets of EPR (Table 5) are often the more difficult to manage or expensive elements of the waste stream (Driedger 2002). Plastics (especially plastic packaging), by some accountings, are more expensive to manage than other elements of the waste stream, especially through recycling (Nakajima and Vanderburg 2006). If this is indeed the case, which is far from clear, then even though revenues from recycling would be lost, shifting plastics management to composting might be an overall cost reduction – but not if in-vessel management is required, as is the case in the UK (Song et al. 2009).

**Table 5. Targets for EPR in Beyond Waste (the NY State solid waste management plan)**

<table>
<thead>
<tr>
<th>Target</th>
<th>Legislation Passed? Introduced?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronics</td>
<td>Effective 4/11</td>
</tr>
<tr>
<td>Reusable Batteries</td>
<td>Effective 7/11</td>
</tr>
<tr>
<td>Pharmaceuticals</td>
<td>Introduced, 2011 session</td>
</tr>
<tr>
<td>Household hazardous waste (HHW)</td>
<td></td>
</tr>
<tr>
<td>Packaging</td>
<td></td>
</tr>
<tr>
<td>Mercury-containing products</td>
<td>Introduced, 2011 session</td>
</tr>
<tr>
<td>Paint</td>
<td></td>
</tr>
<tr>
<td>Automobiles</td>
<td></td>
</tr>
<tr>
<td>Carpet</td>
<td></td>
</tr>
<tr>
<td>Office Furniture</td>
<td></td>
</tr>
<tr>
<td>Roofing shingles</td>
<td></td>
</tr>
<tr>
<td>Appliances</td>
<td></td>
</tr>
<tr>
<td>Tires</td>
<td></td>
</tr>
</tbody>
</table>

EPR also offers waste managers the potential to shift costs from all taxpayers to those who use particular materials. Normally, this assessment is based on the standard waste management costs associated with collection from waste generation points and subsequent management of the materials. However, the management of litter, which has such a close
association with plastics (especially plastics packaging), is no one’s explicit responsibility, although various levels of government do assume it. Estimates of annual terrestrial litter management costs in the US were $11.5 billion (Mid Atlantic Solid Waste Consultants 2009), and, in Australia, Aus$200 million/yr (ExcelPlas Australia et al. 2004). Marine litter management, if undertaken, would seem likely to cost at least as much, with one estimate for cleanups along the California coast alone being $500 million (Rochman et al. 2013). Considering degradable plastics as an acceptable means of addressing EPR could allow manufacturers to avoid further end-of-life responsibilities. Those working toward packaging EPR legislation in the US (Gardner 2013) understand that packaging EPR may provide a financing mechanism for litter, particularly litter that might reach the marine environment (personal communication, H. Sanborn, Executive Director, California Product Stewardship Council, 10 May 2011). Thus, degradable plastics appear technically unable to address marine litter, and their adoption as an EPR alternative could impede assigning the costs of clean-up to manufacturers.

### 6.6 Zero Waste

“Zero waste” is a waste (and materials) management planning approach that has been adopted by a number of governments around the world; the most prominent among them are New Zealand and San Francisco (Greyson 2007). Zero waste requires changing materials management from a linear process (extraction-processing-use-discard) to a circular process, where inputs for new products come from those things that are no longer needed. The infused paradigm is to mimic how natural systems reprocess nutrients (McDonough and Braungart 2002).

Re-use and waste avoidance are primary elements of a zero waste system in order to minimize energy losses. Recycling is de-emphasized, as recycling requires energy supplements
and also tends to produce products that have reduced value (“downcycling”) (McDonough and Braungart 2002). Composting is welcomed in one sense, as the recovery of organic matter back into organic matter that may support agriculture is clearly part of a sustainability program; however, losing the embedded energy in manufactured goods and re-purposing them as compost does not jibe with the essential program of maintaining materials in the form they are in, as is possible. In addition, re-use and creative remanufacturing using discards depends upon waste stream simplification (McDonough and Braungart 2002); at least initially, increasing use of degradable plastics creates materials complications (unless/until all plastics were made from degradable polymers).

Table 6 summarizes the impacts of degradable and compostable plastics on future and potential waste management systems.

**Table 6. Impacts of degradable and compostable plastics on future and potential waste management systems**

<table>
<thead>
<tr>
<th>Waste Management System</th>
<th>Compostable Plastics</th>
<th>Degradable Plastics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expanded Recycling</td>
<td>Increase resin complexity, cause recyclate quality issues</td>
<td>Increase resin complexity, cause recyclate quality issues</td>
</tr>
<tr>
<td>Expanded Organics Recovery</td>
<td>If aerobic, would decrease-eliminate product contamination; cause product contamination in anaerobic environments (perhaps not starch-based resins)</td>
<td>Cause product contamination</td>
</tr>
<tr>
<td>Innovative Energy Recovery</td>
<td>No impact</td>
<td>No impact</td>
</tr>
<tr>
<td>Bioreactor Landfill</td>
<td>No positive effects</td>
<td>Slight positive effect from bag failures</td>
</tr>
<tr>
<td>Extended Producer Responsibility</td>
<td>Not compliant with many key elements; may conflict with opportunities to recover marine litter control costs</td>
<td>Not compliant with many key elements; may conflict with opportunities to recover marine litter control costs</td>
</tr>
<tr>
<td>Zero Waste</td>
<td>Conflicts with precepts to minimize losses of embedded energy</td>
<td>Conflicts with precepts to minimize losses of embedded energy</td>
</tr>
</tbody>
</table>
7. Conclusions

Although all polymers will degrade under certain conditions, plastics that are specifically designated as degradable have been manufactured to do so in an enhanced way. Degradable plastics are supposed to lose important materials properties within days-weeks-months after intended usage has been completed. The extent to which the plastic physically changes and then is consumed by biota varies for different formulations, sometimes intentionally. The first plastics marketed as degradable tended not to meet user expectations within expected timeframes. Thus, around the turn of the century various groups and agencies established sets of standards that manufacturers were expected to meet in order to make certain product claims.

Degradable and compostable plastics have been created to primarily address two issues associated with conventional plastics: their process contamination of compost, and the persistence of plastics as litter. Compostable plastics, a subset of degradable plastics, are manufactured so as to become indistinguishable from other organic compounds treated through managed aerobic decomposition. Visible and chemical pollution of the humus that results from composting has been a process issue since large-scale composting began to widely adopted in the 1980s. It is thought the use of plastics that meet compostable standard will eliminate these problems. However, conditions that lead to the degradation of compostable plastics are not sustained at most small and/or backyard compost piles, and so certified compostable plastics again are not meeting user expectations in many cases.

Most litter does not accumulate at sites where industrial compost conditions exist, so compostable plastics tend not to be identified as the means to eliminate litter effects. It has been suggested that plastics where degradation can be initiated under less stringent conditions may help to minimize litter impacts. Those plastics that begin degrading due to UV light exposure
appear to have the most promise in causing less litter effects, since much objectionable litter is found outside. However, it is not clear that UV-initiated degradation results in fragments that are palatable to organisms. It also is not clear that "oxo-degradable" plastics break down quickly or completely enough to affect litter, either.

At best, degradable plastics only create small, insignificant benefits in other waste management processes; more generally, they just seem to create complications. They may become substantial impediments to plastics recycling if they grow to be a substantial portion of plastics markets. Some see degradability, in and of itself, as a necessary feature of increased materials sustainability, although the reasoning for this position is not well articulated. Therefore, it is difficult to perceive of degradable plastics as being much more than an ineffective solution addressing a subset of the significant issues associated with modern materials' selection and management processes.
Acknowledgements

The authors have received support from the Town of Brookhaven through the Center for BioEnergy Research and Development. Although the Town of Brookhaven financially supported some of the research described in this article, it does not necessarily reflect the view of the Town and no official endorsement should be inferred. The Town makes no warranties or representations as to the usability or suitability of the materials and the Town shall be under no liability for any use made therefrom.
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