Degradable Plastics and their Potential to Affect Solid Waste Systems

Krista L. Thyberg
SUNY Stony Brook, david.tonjes@stonybrook.edu

David J. Tonjes
SUNY Stony Brook, david.tonjes@stonybrook.edu

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K.L. Greene[1], D.J. Tonjes[1]
[1]*Department of Technology and Society, Stony Brook University, USA*

Abstract

Plastic waste forms a substantial part of municipal solid waste and has caused environmental concerns, particularly due to chemical contamination of the environment and effects from persistent litter. Plastics also complicate waste management processes, such as by having poor recovery rates through recycling, and causing contamination in composting operations. One potential means to address some of these challenges is through degradable plastics which, unlike conventional plastics, are designed to decompose at an accelerated rate in specific environments. Degradable plastics aim to address the end-of-life of plastic products and are intended to reduce the environmental impacts associated with their use and management. 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 labelled 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, user confusion regarding degradable definitions is 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, they may be more harmful than helpful to waste management systems at this time. Here we discuss how these materials perform in different aspects of solid waste programs: recycling, composting, WTE incineration, and landfills, as well as the potential for these plastics to reduce litter problems, both on land and at sea.

Keywords: Compostable plastics, degradable plastics, municipal waste management, composting

1 Introduction

Plastics are integral elements of modern life and have been in use for over 150 years [1]. Their ubiquity is increasing; one estimate was that 300 million tonnes of plastics were produced worldwide in 2012 [2]. The versatility of plastic materials enables them to be used for many applications, although packaging and single use consumer products are the most widespread uses. One estimate is such items are 35%-45% of all plastics production [3]. 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 [1]. These same properties, however, impede their disappearance in the environment, creating continuing concern over environmental impacts [2]. Conventional plastics may require decades or longer to degrade [4], and the degradation process may release additives and by-products that pose threats to the health of organisms (including people) to the degree that there has been a call to declare plastics hazardous materials [2].

1.1 Negative Impacts of Plastics

Negative aspects of plastics are often enmeshed in waste management processes. Chemical variation in resin types can make reuse and recycling difficult [5, 6]. Plastics create management difficulties at composting plants, both as contaminants at yard waste sites due to waste collection in plastic bags, and for general efforts to promote food and MSW composting, because of plastic disposable utensils and plate ware [7, 8]. 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 [9], have been found in landfill leachates [10], 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. Plasticizers that are removed from influents contaminate sewage sludges, and the trend towards greater reuse of sludges means wide distribution of them to agricultural soils [11]. Incineration of chlorinated plastics has been linked to enhanced dioxin generation [12].

Litter (improperly disposed goods) often contains large amounts of plastic [7]. Plastic bags are extremely mobile: their high surface area to weight ratio creates sail-like materials. Most plastics are less dense than water and are hydrophobic so they can be transported long distances after reaching water bodies because they float and do not become waterlogged [13]. 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 [4]. Additionally, floating plastics may gain fouling biofilm that inhibits further exposure to sunlight [14]. Few microorganisms can use plastic polymers for sustenance, especially when the polymers are intact [4]. Thus, plastic litter, especially in marine settings, is notably persistent and often seems to remain visible forever. Entanglement and envelopment in plastic debris affects organisms and floatable materials can serve as simulacra of prey, as demonstrated by surveys of charismatic marine species documenting ingestion of plastic [14]. The visible portion of litter may not be the greatest problem, however, as a greater mass of plastic is present in the "microlitter" fraction [13]. 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 [15]. 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 [16], and impacts may be underestimated as many affected organisms sink or are consumed by predators [17].

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 life makes this difficult to implement. 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 [18], or were voluntarily foresworn (e.g., McDonald's clamshells). Plastic bags have been legislated against in various places, such as in Ireland in 2002. The plastics industry has responded by establishing and supporting recycling programs [5, 6]. 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 aluminium containers [19, 8]. Packaging product stewardship programs (plastics constitute a major element of packaging and are often perceived as the constituents causing the most problems) have been adopted in Germany, generally across the European Union, and in Japan, Taiwan, South Korea, Brazil, and Peru [20], and in British Columbia, Nova Scotia, and Ontario provinces, Canada. 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 [2].

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. Degradable plastics are expected to address litter problems and to coexist better with composting efforts [21]; degradable plastics may also generate benefits when landfilled, although it is unclear if degradation is always optimal in landfills. The compatibility of degradable plastics with conventional reuse and recycling programs remains a problem [22, 23, 6], 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, 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 and then considering whether these products have appropriate specifications that are either compatible with or improve current waste systems.

2 Degradable Plastics

2.1 History

In the late 1980s, several US plastics companies began to market products that were “degradable” (they were intended to last in the environment for less than the life-span of normal plastics) [24]. Degradation meant the loss of properties, such as physical strength and integrity, not necessarily the total elimination of polymeric structures. To achieve this, transition state metals, carbonyls, and carbon monoxide groups were inserted into some polymers, creating greater photosensitivity, and degradation was expected to continue enough so that the remaining fragments might be consumable by microorganisms. However, when these plastics went through composting facilities, sewage treatment plants, or were used in agriculture, they only disintegrated into fragments and did not completely mineralize into carbon dioxide and water, leaving significant amounts of plastic behind [25]. Because UV-sensitive plastics did not meet consumer expectations of “disappearing” after use, other approaches, such as starch insertion into polymer chains, were undertaken. 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) [26].

The late 20th century enthusiasm for degradable plastics faded when product degradation not meeting expectations. Output began to grow again in the late 2000s and has continued. The second wave of degradable plastics is used in packaging, disposable food utensils, bags, mulch films, and diapers [24, 27]. Only a few durable goods are made from degradable plastics, as it can be difficult to suppress degradability until disposal for long-lived products [21]. The most common, successful degradable resins are poly-lactic acid (PLA), polyhydroxyalkanoate (PHA), and starch-based polymers. PLA is synthesised by either condensation polymerization, azetropic dehydrative condensation of lactic acid, or by ring-opening polymerization of lactide. PLA’s monomer, lactic acid, is obtained by chemical synthesis or fermentation of carbohydrates [28]. PHA polymers are synthesized inside microorganisms in a carbon-augmented environment [29]. PHA is also produced by genetically modified organisms. Thermoplastic starch is obtained by the destructurization of native starch in the presence of plasticizers. It may be used on its own or in combination with other polymers to improve mechanical properties. Other currently marketed degradable resins include starch-inserted conventional, UV-initiated, and oxo-degradable plastics.

2.2 Standards

The failure of early biodegradable plastics to degrade as completely as expected led to the development of industry standards, intended to ensure that degradable expectations are met [27]. Generally, these standards describe the terminology, definitions, and testing guidelines for materials [30] with the intent of providing consistency, accountability, and the reliability of plastic materials with regard to their disposal. Different but similar approaches have been enacted in the US, Germany, Japan, and the European Union, and an international code has been developed by the International Organization for Standardization (ISO) [27].

The American Society for Testing and Materials (ASTM) promulgates acceptable usage through Committee D20.96, "Environmentally Degradable Plastics and Biobased Products," leading to two 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). These standards define compostable plastics operationally based on conditions found at municipal and industrial compost facilities [27], according to three tests: 1) conversion to CO_2 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). ASTM has also developed the standard D7081 for non-floating biodegradable plastics in the marine environment. Certification programs based on these standards have been developed to issue a certification guaranteeing that a material meets standard requirements [27, 30]. The primary European standard, EN 13432, and its companion standards 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, and result in a product that is recognizably compostable by the compost "end user" without toxic by-products [7,27].

3 Compatibility of Degradable Plastics with Current Waste Management Processes

3.1 Composting

Compostable plastics require specific levels of moisture and oxygen for initial reactions to occur to make the polymers consumable by bacteria [21]. These conditions are usually only found in larger, industrial facilities. There materials are regularly turned and usually have been pre-processed [30]. 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 residual organic matter (humus), some of which is biomass associated with the microbial and macrobiota consumers and the rest is relatively indigestible organic matter. Thus, performance standards for 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; in other jurisdictions, the typical requirement is to "degrade to the degree that compost inputs do" [21]. Standards often add an element of toxicity testing [7, 31], minimizing the potential for the compost product to cause harm to plants, animals, and/or humans.

Certified compostable plastics in standard, large-scale composting practices have been found to degrade well with different kinds of substrates such as manure, yard, and food waste [30], and with different technologies, such as turned windrow or in-vessel [31]. Compostable mulch films are another area where compostable plastics are perceived as technological advances, as dirt adhesions to the films make them difficult to recycle but may actually enhance compostability.

However, reports of failure of certified compostable plastics to perform in home and smaller scale composting environments are common. Inadequate temperatures in smaller piles, so that the key hydrolysis reaction for PLAs is not initiated, are cited as the reason for much of the poor results [21]. This has reignited controversies associated with earlier degradable plastic products due to the mismatch between producer claims and consumer experiences. The adoption of compostable plastic collection bags may be limited because jurisdictions need to ensure formulations are compatible with the system accepting the waste and bags.

Composting plastics minimizes the amount of waste going to landfills which has been a major public policy initiative for decades. USEPA [8] 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 through composting. Contamination of yard wastes by plastic bags is a major operational inconvenience, and institutional food waste composting requires removal of unwanted plastic cutlery and the like. Compostable plastics are perceived as means to address these issues.

There are concerns that composting plastics invalidates the resulting compost for organic certification and subsequent use on organic farms. Tentative organic certification rules require specification of the source of the feedstock for the plastic. Only allowing plant-based degradable plastics may be complicated to implement. A primary purpose of compostable plastics is to support greater composting use; however, it is not clear that these 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 and small scale usage.

In summary, certified compostable plastics have been shown to fully degrade in most large scale composting environments, where they allow for reductions in the amount of waste being disposed, can facilitate food and yard waste collection efforts, and contribute to the creation of a valuable end product (compost). However, they have been shown to not fully degrade in smaller scale composting sites, and there is uncertainty as to whether they can be used in organic farming. Furthermore, other degradable plastics that do not meet compostable standards will not achieve the benefits associated with compostable plastics, and can cause confusion whether plastics can be inputs in composting facilities. This confusion can lead to compost contamination if non-certified products are treated at composting facilities, or abstention from compostable plastics use.

3.2 Recycling

Recycling is the primary method used to minimize waste in landfills; it is perceived to be the most preferable means of managing plastics. However, many resins are difficult to recycle [5] because certain resins are intolerable contaminants for other resins, and high volume-weight ratios for some plastics make collection and transport difficult and expensive [6]. Sorting plastics to general resin categories can be challenging [5]; many plastics products look similar but are of different compositions, and some plastic wastes are small and difficult to handle.

Degradable versions of products differ from conventional plastics in either base polymers or additive mixtures; this means their inclusion in recycling processes will increase input heterogeneity, reducing recovered plastic quality. 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 for instance [31]. Reports from Australia suggest that recyclers do not want to accept degradable plastics because they result in a loss of plastic properties could result in the degradation of these products [23]. On-going degradation of plastics makes the resulting recycled product even less suitable for reuse [6, 21]. However, the current consensus appears to be that degradable plastics do not result in poorer recycled products if they constitute only a very small part of overall feedstock [22, 21]. They may become substantial impediments to plastics recycling if they grow to be a substantial portion of plastics markets. Generally, degradable plastics do not appear to provide any benefit to recycling systems and are likely to reduce the value of recycled materials created from streams containing many degradables.

3.3 Waste-to-Energy Incineration

The processes in waste-to-energy (WTE) incineration would not be substantially affected by whether input plastic is degradable or not. However, the use of bio-based resins would reduce fossil CO_2 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 CO_2 in the biosphere [32]. 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 compared to the general grid mix of energy sources, 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 efficient, although it is an unintended, beneficial side effect.

Many degradable plastics are made from renewable feedstocks [33]; the production of conventional plastics uses 4% of the world's annual petroleum production [1]. Therefore, increasing the market share of degradable plastics would slightly reduce demands on petrochemical reserves [33]. Finally, harmful air emissions resulting from WTE may be reduced if fewer potentially toxic additives (e.g. chlorinated compounds leading to dioxin releases) are used in plastics production.

3.4 Landfilling

Replacing conventional plastics with degradable plastics may result in greater degradation of the plastics within a landfill if the degradable plastics encounter conditions that result in depolymerization. Moisture may or may not be available in particular landfills, but landfills generally are known to be lacking in oxygen so any plastics degradation must occur anaerobically. It has been suggested anaerobic decay of some degradable plastics is possible. This could lead to increased methane emissions if gas collection is not present. It also is likely that most degradable plastics will not behave very differently from petroleum-based plastics in most landfills. Burial of UV-sensitive plastics is not likely to result in any early plastics decay. Most compostable plastics generally require moisture and oxygen for the process to proceed very far, so they too will not degrade rapidly.

The lack of degradation of organic material in a landfill have been identified as a climate change benefit because no or slow decay of organic matter represents a sequestration, especially if retarded for centuries or more. Therefore, plastics that degrade in landfills may actually reduce overall environmental benefits. 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; and 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 sequestration of biobased plastics represents a drawdown in current stocks of circulating CO_2.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.

3.5 Litter

The persistence of plastics when inappropriately strewn into the environment makes plastics the poster-child for litter [2]. It has been argued that if plastics were degradable, even at timescales of several years, it would reduce the impact of litter tremendously [34]. However, it has also been asserted that most compostable plastics do not degrade very well outside of compost piles [21].

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 with most litter [7]. 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 compostable 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 degradable materials often did not degrade entirely, and neither did the PHB-coated cups. PHB films had approximately similar results [35].

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 do not retain 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. 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 that was tested was still cohesive after 40 weeks of exposure, although it had lost some mass. However, a starch-based compostable plastic degraded enough to lose its integrity before fouling occurred [36]. 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 [31] 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 CO_2) or a residue will be created. The recalcitrant residues should be characterized, both chemically and in terms of their potential environmental effects, 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 [23]. 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 [2]. Therefore, plastics that only partially degrade still represent substantial environmental problems if they become litter [26].

4 Conclusion

Degradable and compostable plastics have been created primarily to address two issues associated with conventional plastics: their process contamination of compost and the persistence of plastics as litter. Compostable and degradable plastics are achieving some of these benefits, but they are far from a perfect solution at this time. In other waste management processes, such as recycling or landfilling, degradable plastics only create small, insignificant, benefits; generally, they just seem to create complications. It can be concluded that degradable and compostable plastics do not achieve any substantial advantages at this time and are not fully sustainable. This assessment might change as resins are better designed, and if consumers understand the importance of certification schemes. It is likely that the reason for slow adoption of degradable plastics is their poor performance, high cost, confusion among users, and complications in waste treatment systems.

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