Appendix 1 – Credentials and Expertise

I hold the MSU University Distinguished Professorship at Michigan State University in the Department of Chemical Engineering & Materials Science. I have 130 refereed publications in leading journals, 25 issued patents, edited three books and one expert dossier -- all in the area of bio-based renewable polymeric materials. My research encompasses design & engineering of sustainable, biobased products, biodegradable plastics and polymers, biofiber reinforced composites, reactive extrusion polymerization and processing. I have active research studies in plastic end-of-life options like biodegradation and composting. My research involves developing carbon and environmental footprint of biobased and biodegradable plastics and products and was instrumental in developing methodology for measuring biobased carbon content (ASTM D6866). I am also active in LCA (life cycle assessment) methodology development. Under my supervision, 22 students have obtained their Master's degree, 15 students their Ph.D. degrees and six are working towards their Ph.D.

I chair the ASTM committee D20.96 on biobased and biodegradable plastics and served on the Board of Directors of ASTM International. The Standards discussed in the Guide on compostability, biodegradability, and biobased are from D20.96. I also serve as the USA technical expert to ISO (International Standards Organization) committees TC 61/WG 5 on biodegradability in Plastics, and Chairman of ISO TC 61 SC 1 on Terminology. I am Convener of working group 7 (Recovery of Packaging through organic recycling) of ISO TC 120 SC 4 on Packaging and the Environment. I have testified before U.S. congressional hearings on the biodegradable and biobased plastics. I serve as the Scientific Chair of the Biodegradable Products Institute (BPI).

Appendix 2 –Rationale for developing ASTM D6400 and D6868 and about ASTM

ASTM D6400 and the complimentary Standard D6868 was developed in response to U.S. Federal Trade Commission (FTC), a group of state attorneys general, state legislatures, and the U.S. Congress becoming concerned about the various degradability and environmental claims being made, especially as they related to existing waste management practices for example biodegradability under composting conditions. It was not in response to manufacturers' increased production of plant-based plastic resins (ref 220), or the desire to contrast them with petroleum-based plastics (ref 221) as discussed in the Guides. In fact, the largest selling compostable plastic is the petro based poly butylene adipate-co-terephthalate (PBAT, BASF' Ecoflex). It is completely utilized by microorganisms in compost environments as documented by ASTM D6400.

The committee ASTM D20.96was formed to develop science based Standard test methods and specifications (pass/fail criteria). It has 100+ technical experts from Government, industry, and academe.

About ASTM

ASTM is a one-hundred-and-twelve year old forum for the development and publication of voluntary consensus standards. It is one of the largest voluntary standards developing organizations (SDO) in the world and the largest U.S.-based SDO. Thousands of ASTM standards are used around the world as the basis of regulations and as essential elements of trade between nations. ASTM is the most frequently cited SDO in the ***U.S. Code of Federal Regulations*** **with over 2360 standards cited there and used for federal government procurement.** Over 5000 ASTM standards are used in 75 nations as the basis of national standards, are directly adopted or are cited as references.

Appendix 3 -- Science of Composting

Composting is a “managed process” in which microorganisms break down organic matter (that could include the “compostable products” which is the subject of this discussion) and produce carbon dioxide, water, heat, and humus, the relatively stable organic end product. Composting, typically, proceeds through three phases: 1) the mesophilic, or moderate-temperature phase, which lasts for a couple of days, 2) the thermophilic, or high-temperature phase, which can last from a few days to several months, and finally, 3) a several-month cooling and maturation phase. There maybe variants to this process in terms of temperature, and time as the discussed in the FTC guides but the basic science and biology will not and cannot change.

Compostable products meeting ASTM D6400/ASTM D6868 ensures that they are **completely** consumed (assimilated) by the microbes present in compost. They function as **food for the microorganisms** providing it with **energy** to drive their life processes, and thereby promoting the regular composting process. At the end of the compost period there is no compostable product remaining, they are all consumed by the microorganisms in the composting process and **become part of the microorganisms.** Mechanistically, the product is transported into the microbial cells where they are oxidized to CO_2, releasing energy for the microbial life processes. Note that the ASTM Specification Standards require that **all** of the substrate carbon should be consumed by the microorganisms leaving no persistent or toxic residue

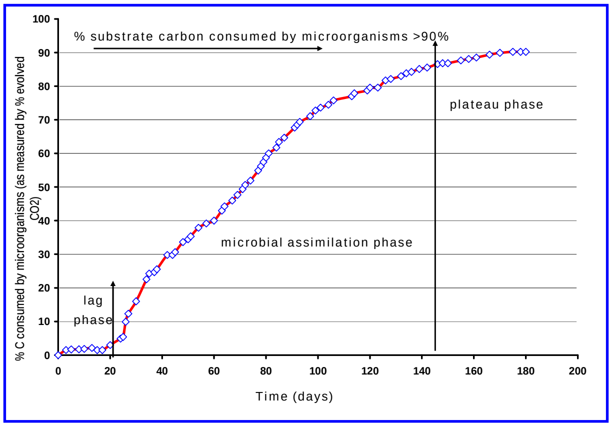
Microbial chemistry:

Microorganisms extract chemical energy for use in their life processes by the aerobic oxidation of glucose and other readily utilizable substrates. They do so by transporting the carbon substrate inside the cell, oxidizing the substrate carbon to CO_2, which release 686 kcal/mol of energy. This energy is harnessed by the microorganisms in a specialized cellular process requiring the participation of three metabolically inter-related process – Tricarboxylic acid cycle (TCA cycle), electron transport, and oxidative phosphorylation.

AEROBIC

$$\text{Glucose/C-bioplastic} + 6\,O_2 \longrightarrow 6\,CO_2 \uparrow + 6\,H2O;\ DG^{0'} = -686\ \text{kcal/mol}$$

Thus, a measure of the rate and amount of CO_2 evolved in the process is a direct measure of the amount and rate of microbial consumption/use (biodegradation) of the C-polymer.

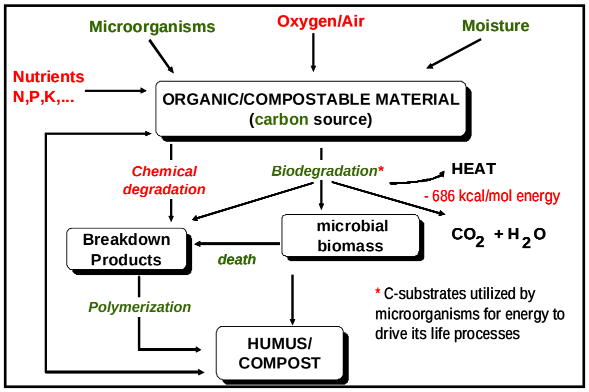


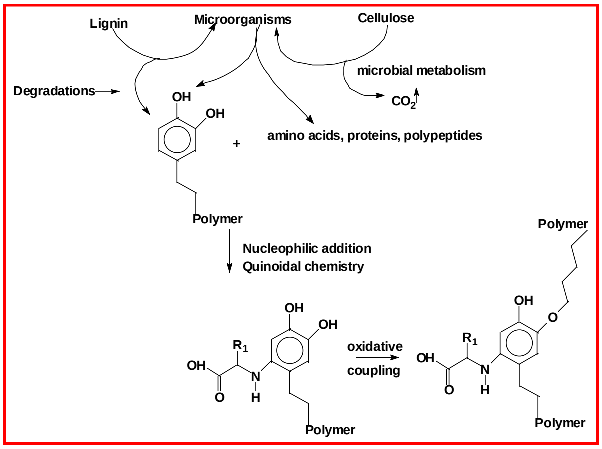
ASTM standards D6400, D6868 are based on the above science. The Standard calls for testing the compostable plastic as the **sole carbon source** in a compost environment and measuring the percent carbon of the test substrate being consumed by the microorganisms as measured by the evolved CO_2. The attached figure shows typical data obtained when the per cent carbon released (as CO_2) from a compostable plastic exposed in a composting environment is plotted as a function of time.

More importantly, the ASTM Standards require testing for eco and phyto toxicity, and regulated metals, thereby ensuing meeting the NOSB requirement that compost produced “do not contribute to contamination of crops, soil, or water by plant nutrients, pathogenic organisms, heavy metals, or residues of prohibited substances”.

Role of compostable products in composting process:

The attached figure shows the principal biochemistry and chemistry processes occurring in a composting process. The composting process is not merely the biodegradation of organic matter, although it is the first step in the process. Readily utilizable carbon substrates like food wastes are consumed by microorganisms as energy to drive their life processes. The carbon substrates are broken down to smaller molecules by abiotic and biotic processes. These small molecules are transported inside the cell. The transportation process is governed by not just molecular weight (or how small the molecule is) but by other factors like hydrophobic-hydrophilic balance, molecular and structural features. As discussed earlier, the carbon molecules are biologically oxidized to CO_2 in a complex cellular process which releases energy that is harnessed by the microorganism for its life processes. As can be seen from the attached figure, it is the second stage of the composting process, namely the complex polymerization process occurring between breakdown products from the lignin degradation and microbial cell death that results in the formation of humic substances called compost. The chemistry of this process arising from complex reactions between lignin breakdown products (from the lignocellulosic substrates) and the proteins, polypeptides, and amino acids from the microbial cell death is schematically shown in the attached figure. It is important to recognize that one cannot and should not interfere or change the **natural** complex humic/compost formation process.





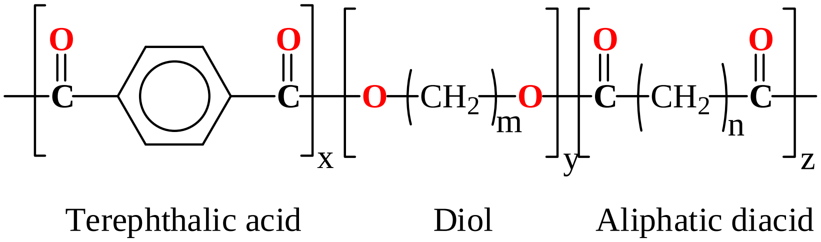
Compostable plastics (that meet ASTM/ISO standards) are required to be completely metabolized by the compost microorganisms as documented by the compostable plastics carbon conversion **completely** to CO_2. The compostable plastic does not take part or interfere in the natural complex chemical processes occurring.

Therefore, compostable plastics that meet ASTM D6400 (Standard Specification for Compostable Plastics), and ASTM D6868 (Standard Specification for biodegradable plastics used as coatings on paper and other compostable substrates) fully comply with the NOSB requirements; will not be detrimental to the composting process, and functions as an additional food/energy source for the microorganisms.

Exemplars showing complete assimilation of the compostable plastics carbon by microorganisms as measured by the test substrate's carbon conversion to CO_2 using ASTM/ISO Standards

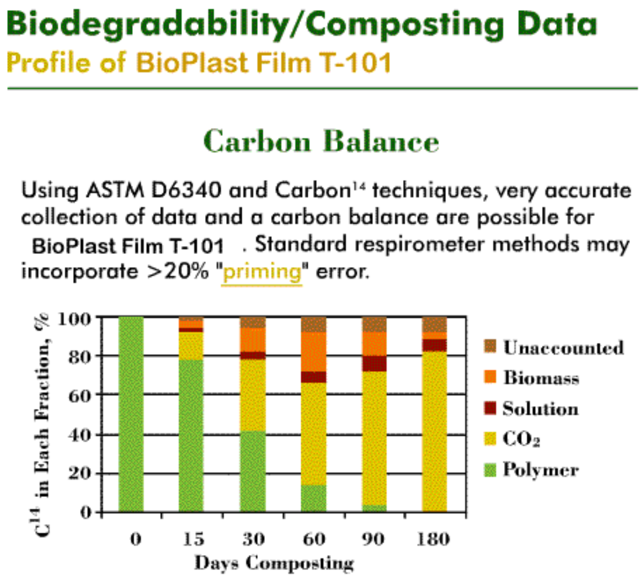
Poly butylene adipate-co-terephthalate (PBAT)

C-14 labeled PBAT – showing the complete utilization of the most recalcitrant aromatic carbon by compost microorganisms by labeling the aromatic carbon with C-14 and conducting a complete carbon-14 balance.



Copolyester

C-14 label on aromatic ring carbon for monitoring biodegradability



Biodegradability/Composting Data

Profile of BioPlast Film T-101

Carbon Balance

Using ASTM D6340 and Carbon¹⁴ techniques, very accurate collection of data and a carbon balance are possible for BioPlast Film T-101 . Standard respirometer methods may incorporate >20% "priming" error.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Biodegradable and compostable alternatives to conventional plastics

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doi: 10.1098/rstb.2008.0289

This journal has a very impact factor of 5.1 and ranked 6th amongst 76 journals in Biology.

For composting see section 4 and onwards

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B

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Biodegradable and compostable alternatives to conventional plastics

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Packaging waste forms a significant part of municipal solid waste and has caused increasing environmental concerns, resulting in a strengthening of various regulations aimed at reducing the amounts generated. Among other materials, a wide range of oil-based polymers is currently used in packaging applications. These are virtually all non-biodegradable, and some are difficult to recycle or reuse due to being complex composites having varying levels of contamination. Recently, significant progress has been made in the development of biodegradable plastics, largely from renewable natural resources, to produce biodegradable materials with similar functionality to that of oil-based polymers. The expansion in these bio-based materials has several potential benefits for greenhouse gas balances and other environmental impacts over whole life cycles and in the use of renewable, rather than finite resources. It is intended that use of biodegradable materials will contribute to sustainability and reduction in the environmental impact associated with disposal of oil-based polymers.

The diversity of biodegradable materials and their varying properties makes it difficult to make simple, generic assessments such as biodegradable products are all 'good' or petrochemical-based products are all 'bad'. This paper discusses the potential impacts of biodegradable packaging materials and their waste management, particularly via composting. It presents the key issues that inform judgements of the benefits these materials have in relation to conventional, petrochemical-based counterparts. Specific examples are given from new research on biodegradability in simulated 'home' composting systems. It is the view of the authors that biodegradable packaging materials are most suitable for single-use disposable applications where the post-consumer waste can be locally composted.

Keywords: biodegradable; compostable; biopolymers; packaging; environment; waste management

1. INTRODUCTION

Many different materials are used for packaging including metals, glass, wood, paper or pulp, plastics or combinations of more than one material as composites. Most of these enter municipal waste streams at the end of their service life. Over 67 million tonnes of packaging waste is generated annually in the EU, comprising about one-third of all municipal solid waste (MSW) (Klingbeil 2000). Plastics contribute 18 per cent of the 10.4 million tonnes of packaging wastes produced annually in the UK (DEFRA 2007). Discarded packaging is also a very obvious source of litter, posing a major waste management challenge (see Barnes *et al.* 2009; Gregory 2009; Oehlmann *et al.* 2009; Ryan *et al.* 2009; Teuten *et al.* 2009; Thompson *et al.* 2009*a*,*b*).

In recent years, the recycling of packaging materials has increased but the recycling rates for most plastic packaging remain low (Davis & Song 2006; Hopewell *et al.* 2009). A large number of different types of polymers, each of which may contain different processing additives such as fillers, colourants and plasticizers, are used for packaging applications (Andrady & Neal 2009; Thompson *et al.* 2009*a*). These composition complexities together with contamination during use often render recycling uneconomic compared with disposal in landfill. Although the proportion of waste being landfilled has fallen in recent years, around 60 per cent of municipal waste in England still ends up in landfill (http://www.defra.gov.uk/environment/statistics/wastats/bulletin07.htm). This presents environmental concerns, resulting in strengthening of regulations on waste (e.g. Packaging and Packaging Waste Directive (94/62/EEC) and UK Packaging Regulations (1998).

Biodegradable plastics with functionalities and processabilities (Bioplastics 07/08) comparable to traditional petrochemical-based plastic have been developed for packaging applications (e.g. www.european-bioplastics.org). Typically, these are made from renewable raw materials such as starch or cellulose. Interest in biodegradable plastic packaging arises primarily from their use of renewable raw materials (crops instead of crude oil) and end-of-life waste management by composting or anaerobic digestion to reduce landfilling (Murphy & Bartle 2004). The disposal of packaging materials is particularly significant in view of the recent focus on waste generation

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One contribution of 15 to a Theme Issue 'Plastics, the environment and human health'.

and management as important environmental aspects of present-day society (DEFRA 2004; Thompson *et al.* 2009*b*).

In addition to performance and price, biodegradable plastics must offer advantages for waste management systems in order to realize an overall benefit. This paper discusses the potential impact of biodegradable plastics, with particular reference to packaging, and waste management via landfill, incineration, recycling/reuse and composting. It provides an overview of the key life cycle issues that inform judgements of the benefits that such materials have relative to conventional, petrochemical-based counterparts. Specific examples are given from new research on biodegradability in simulated 'home' composting systems.

2. BIODEGRADABLE ALTERNATIVES TO CONVENTIONAL PLASTICS

Biodegradable polymers (*BDPs*) *or biodegradable plastics* refer to polymeric materials that are 'capable of undergoing decomposition into carbon dioxide, methane, water, inorganic compounds, or biomass in which the predominant mechanism is the enzymatic action of microorganisms, that can be measured by standardized tests, in a specified period of time, reflecting available disposal condition' (ASTM standard D6813). A subset of BDPs may also be *compostable* with specific reference to their biodegradation in a compost system, and these must demonstrate that they are 'capable of undergoing biological decomposition in a compost site as part of an available program, such that the plastic is not visually distinguishable and breaks down to carbon dioxide, water, inorganic compounds and biomass, at a rate consistent with known compostable materials (e.g. cellulose)' (ASTM standard D996, also see D6400). Initial steps may involve abiotic (thermal, photo) and biotic processes to degrade the polymer, under suitable conditions, to a low-molecular weight species. However, the resultant breakdown fragments must be completely used by the micro-organisms; otherwise there is the potential for environmental and health consequences (Narayan 2006*a*,*b*). The products of an industrial composting process (typically 12 weeks with an elevated temperature phase over 50°C) must meet quality criteria such as heavy metal (regulated) content, ecotoxicity and lack of obvious distinguishable polymer residues.

Depending on their origins, BDPs may be classified as being either *bio-based* or *petrochemical-based*. The former are mostly biodegradable by nature and produced from natural origins (plants, animals or micro-organisms) such as polysaccharides (e.g. starch, cellulose, lignin and chitin), proteins (e.g. gelatine, casein, wheat gluten, silk and wool) and lipids (e.g. plant oils and animal fats). Natural rubber as well as certain polyesters either produced by micro-organism/plant (e.g. polyhydroxyalkanoates and poly-3-hydroxybutyrate) or synthesized from bio-derived monomers (e.g. polylactic acid (PLA)) fall into this category. Petrochemical-based BDPs such as aliphatic polyesters (e.g. polyglycolic acid, polybutylene succinate and polycaprolactone (PCL)), aromatic copolyesters (e.g. polybutylene succinate terephthalate) and poly(vinyl alcohol) are produced by synthesis from monomers derived from petrochemical refining, which possess certain degrees of inherent biodegradability (Clarival & Halleux 2005 in Smith 2005). This classification differentiates between renewable (bio-based) and non-renewable (petrochemical-based) resources, but it should be noted that many commercial BDP formulations combine materials from both classes to reduce cost and/or enhance performance.

Biodegradable plastics, therefore, often comprise polymer blends that contain partly biogenic (renewable) carbon derived from biomass and partly petrochemical carbon. The per cent biogenic carbon present in a plastic or polymeric product can be readily calculated from the C-14 signature of the product as shown in figure 1 (Narayan 2006*a*,*b*). The carbon dioxide (CO_2) in the atmosphere is in equilibrium with radioactive $^{14}CO_2$. Radioactive carbon is formed in the upper atmosphere through the effect of cosmic ray neutrons on ^{14}N. It is rapidly oxidized to radioactive $^{14}CO_2$, and enters the Earth's plant and animal life through photosynthesis and the food chain. Plants and animals that use carbon in biological food chains take up ^{14}C during their lifetimes. They exist in equilibrium with the ^{14}C concentration of the atmosphere, that is the numbers of C-14 atoms and non-radioactive carbon atoms stay approximately the same over time. As soon as a plant or animal dies, they cease the metabolic function of carbon uptake; there is no replenishment of radioactive carbon, only decay. Since the half-life of carbon is around 5730 years, the petrochemical feedstocks formed over millions of years will have no ^{14}C signature. The quantity of bio-based content can be determined (ASTM standard D-6866) by combusting the test material in a polymer in the presence of oxygen and analysing the CO_2 gas evolved to provide a measure of its $^{14}C/^{12}C$ content relative to the modern carbon-based oxalic acid radiocarbon standard reference material (SRM) 4990c (referred to as HOxII).

After an early pilot plant phase in the 1990s, subsequent upscaling of biodegradable (bio)plastic production by both small specialized and established companies since 2000 has now reached an industrial scale, and significant proportions of established and emerging biodegradable plastics now have renewable rather than petrochemical origins (www.european-bioplastics.org; www.bioplastics24.com). Details on the chemical compositions, production, processing, structure and properties of a wide range of bioplastics used for packaging can be found elsewhere in the literature (e.g. Smith 2005) (paper-based products are traditionally regarded as a separate material group). Current production capacity for biodegradable plastics worldwide is around 350 000 tonnes (Bioplastics 07/08), representing less than 0.2 per cent of petrochemical-based plastic, at approximately 260 million tonnes (Miller 2005). However, the environmental performance benefits are insufficient on their own to enable bioplastic polymers to be more widely used as alternatives to conventional plastics. They also need to be cost-effective, fit for purpose and, ideally, provide unique benefits in use (Miller 2005). Hence, bioplastic polymers have not yet realized their full potential.

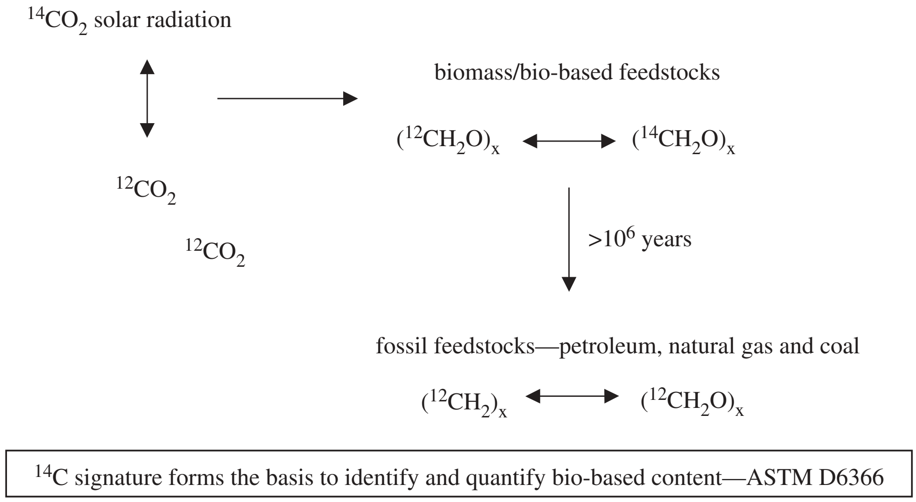

Figure 1. Carbon-14 signature of bio- and petrochemical polymers.

The costs of bioplastic polymers are generally still much higher than that of their traditional plastic counterparts (Petersen *et al.* 1999). Most fall in the range 2–5 € kg^{-1} (Bioplastics 07/08) (compared with approx. 1.2 € kg^{-1} for major petrochemical polymers) and this is a major restriction for more widespread use. However, significant growth rates have been achieved in product capacity over the last decade or so. Bioplastic polymers are expected to become priced more as commodity materials when a critical mass is achieved, driven by a combination of forces including performance and cost improvements, benefits assigned to the use of renewable (bio)resources, increasing oil prices and increasing awareness of environmental impacts and associated legislation.

Processing parameters and technical characteristics of a wide range of commercial bioplastic polymers have been reviewed recently (Bioplastics 07/08). Many bioplastics now have mechanical properties equivalent to that of their conventional counterparts (e.g. polypropylene (PP), polystyrene and polyethylene (PE)) and can be processed using technologies widely used in the polymer industry (e.g. compounding, film processing and moulding). They have found use in many short service life applications where biodegradability is a key advantageous feature (www.european-bioplastics.org) including consumer packaging (e.g. trays, pots, films and bottles in food packaging), convenience food disposables (e.g. cutlery/tableware), bags (shopping, garden or domestic waste), agriculture mulch films, personal-care disposals (e.g. nappies) and even golf tees. Bioplastic polymers have also been used in more durable applications such as in textiles, consumer goods, automotive parts and building and construction where the focus is on the use of renewable (bio)resources and any inherent biodegradability properties need to be suppressed or controlled by careful design.

Bio-based versus biodegradable: it is important to recognize that not all bio-based polymer materials are biodegradable and vice versa. Equally, it is important to recognize that attributes like biodegradability of a given polymer need to be effectively coupled with appropriate waste management in order to capture maximum environmental benefit. For durable products where biodegradability is not a required element for reasons of performance, safety and product life, alternative methods of disposal like waste to energy or recycling need to be identified. Examples of such durable bio-based polymers are bio-polyurethanes based on polyols from vegetable oils for automotive and farm vehicles (Narayan 2006*a*,*b*), biofibre composites for industrial and automotive applications and recent developments in bio-polyethylene derived from sugar cane via ethanol to ethylene.

3. WASTE MANAGEMENT OPTIONS FOR BDPs

There are many technologies available for the treatment of conventional plastic packaging waste (Tukker 2002) from household waste including: integrated collection and incineration with energy recovery, selective combustion of plastics with high calorific value (e.g. in cement kilns) and use as a reducing agent in blast furnaces or as feedstock for recycling.

Approximately 1 million tonnes of non-bottle domestic mixed plastic packaging waste arise in the UK each year, and this is estimated to increase between 2 and 5 per cent per annum (WRAP 2006, 2008). A ‘Waste Hierarchy’ proposed by the UK government (DEFRA 2007) as guidance for selecting the options to minimize the impact of waste recognizes reduction and reuse as the most favourable options where the aim is to minimize the material consumption or divert materials from waste streams.

The impacts of biodegradable bioplastics, when entering the waste stream and handled by current available options (recycling, incineration and landfill), are assessed briefly below. As BDPs enable a potential option for waste treatment through composting as a way to recover the materials and to produce a useful product as compost, particular attention will be given to composting biopolymers.

(a) ***Recycling***

Biodegradable plastics that enter the municipal waste stream may result in some complications for existing plastic recycling systems. For example, the addition of starch or natural fibres to traditional polymers can complicate recycling processes (Scott 1995; Hartmann & Rolim 2002). Although it is feasible to mechanically recycle some bioplastic polymers such as PLA a few times without significant reduction in properties (Claesen 2005), the lack of continuous and reliable supply of bioplastic polymer waste in large quantity presently makes recycling less economically attractive than for conventional plastics. Finally, for certain applications such as food packaging (e.g. in modified atmosphere packaging of meat products), multilayer lamination of different biopolymers may be necessary to enhance barrier properties, just as in conventional plastics (Miller 2005), and this will compromise recyclability of the scrap during packaging manufacture and of post-consumer waste. The recycling of plastics is considered in more detail elsewhere in this volume (Hopewell *et al.* 2009).

(b) *Incineration with energy recovery*

Most commodity plastics have gross calorific values (GCV) comparable to or higher than that of coal (Davis & Song 2006). Incineration with energy recovery is thus a potentially good option after all recyclable elements have been removed. It is argued that petrochemical carbon, which has already had one high-value use, when used again as a fuel in incineration represents a more eco-efficient option than burning the oil directly (Miller 2005).

Reports by the Environment Committees of the UK Parliament (House of Commons 1993; House of Lords 1994) have supported the view that energy recovery for some types of household plastic wastes is an acceptable waste management option. Trials conducted by the British Plastics Federation demonstrated that modern waste-to-energy plants were capable of burning plastic waste, even those containing chlorinated compounds such as PVC without releasing dangerous or potentially dangerous emissions of dioxins and furans (BPF 1993). In 2005/2006, around 8 per cent (approx. 3 million tonnes) of UK municipal waste was processed through 15 incineration facilities (www.defra.gov.uk/environment/statistics/waste) and over 40 million tonnes were incinerated within the EU in around 230 incineration facilities (Musdalslien & Sandberg 2002). It is envisaged that incineration will face continued resistance in the UK unless the public is convinced about the safety of incineration and its contribution to renewable energy supplies (Miller 2005).

Energy recovery by incineration is regarded as a suitable option for all bioplastic polymers and renewable (bio)resources in bioplastic polymer products are considered to contribute *renewable energy* when incinerated (www.european-bioplastics.org). Natural cellulose fibre and starch have relatively lower GCV than coal but are similar to wood and thus still have considerable value for incineration (Davis & Song 2006). In addition, the production of fibre and starch materials consumes significantly less energy in the first place (Patel *et al.* 2003), and thus contributes positively to the overall energy balance in the life cycle. At present, the lack of scientific data on GCV of bioplastic polymers (e.g. relative importance of moisture content (MC), etc.) makes it difficult to accurately determine their value for energy recovery by incineration—further research in the area is required.

(c) *Landfill*

Landfill of waste plastics is the least favoured option in the UK waste hierarchy. It was attractive historically as it was extremely simple and cheap without necessary separation, cleaning or treatment. Western Europe sent 65 per cent of the total recoverable plastics in household waste (8.4 million tonnes annually) to landfill in 1999 (APME 2002). However, suitable sites for landfill across Europe are running out and public concerns are increasing about the impact of landfill on the environment and health from the amount of toxic materials in land-filled municipal waste and their potential leaching out of landfill sites (Miller 2005). Reducing the quantities of waste that ultimately ends up in landfill has become explicit government policy (e.g. Landfill Directive European Commission 1999/31/EC) in the UK and represents a particularly difficult task to achieve (e.g. approx. 60% municipal waste in England is still landfilled in comparison with approx. 37% in France and approx. 20% in Germany (EEA 2007)).

The landfill of biodegradable materials including bioplastic polymers, garden and kitchen waste presents a particular problem in that methane, a greenhouse gas with 25 times the effect of CO_2, may be produced under anaerobic conditions (Hudgins 1999). While such a 'landfill gas' can and is captured and used as an energy source, The Landfill Directive (99/31/EC) seeks to reduce the total amount of biodegradable municipal waste (BMW) going to landfill in three successive stages eventually to 35 per cent of the 1995 total of BMW by 2020.

(d) *Biological waste treatments: composting or anaerobic digestion*

Unlike conventional petrochemical-based polymers, biodegradable and compostable bioplastic polymers can be composted. This can be via aerobic waste management systems such as composting to generate carbon- and nutrient-rich compost for addition to soil. In the UK, there are now more than 300 composting sites that collectively compost about 2 million tonnes of waste annually (roughly 75% of which is household waste, 5% municipal non-household waste and 20% commercial waste: http://www.organics-recycling.org.uk/). The aerobic biodegradation systems are thus of primary importance for BDPs and are dealt with in detail in the following section of this paper.

Certain BDPs are also suitable for anaerobic digestors whereby biowastes can be converted to methane, which can be used to drive generators for energy production. Published reports on the anaerobic digestibility of biodegradable bioplastics are relatively scarce and these systems are not discussed further here (for further information see Ramsay *et al.* 1993; Mohee *et al.* 2008).

4. BIODEGRADABILITY AND COMPOSTABILITY

Making or calling a product biodegradable has no inherent value if the product, after use by the customer, does not end up in a waste management system

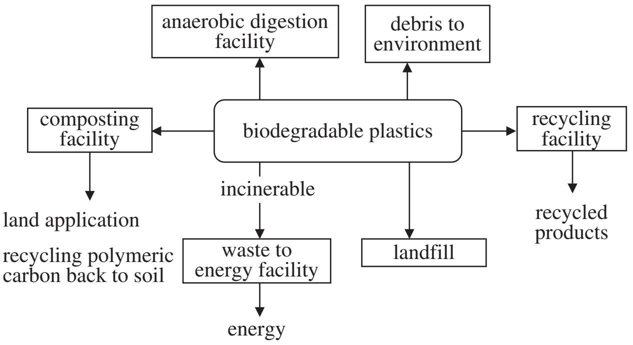

Figure 2. Integration of biodegradable plastics with disposal infrastructures.

that uses the biodegradability features (Narayan 1993, 1994). Figure 2 illustrates the integration of biodegradable plastics with disposal infrastructures that use this biodegradable function of the plastic product.

(a) ***Principles and concepts of composting***

Composting has the potential to transfer biodegradable waste, including biodegradable plastics, into useful soil amendment products. Composting is the accelerated degradation of heterogeneous organic matter by a mixed microbial population in a moist, warm, aerobic environment under controlled conditions. Biodegradation of such natural materials will produce valuable compost as the major product along with water and CO_2. The CO_2 produced does not contribute to an increase in greenhouse gases because it is already part of the biological carbon cycle. Composting is also an important disposal infrastructure because it can receive other bio-based wastes in addition to biodegradable plastics—for example, more than 50 per cent of the MSW stream is typically garden and food waste and non-recyclable paper products.

(i) *Degradable versus biodegradable*

A number of polymers in the market place are designed to be degradable, i.e. they fragment into smaller pieces and may even degrade to residues invisible to the naked eye. While it is assumed that the breakdown products will eventually biodegrade, there are no data to document complete biodegradability within a reasonably short time period (e.g. a single growing season per year). Hence hydrophobic, high surface area plastic residues may migrate into water and other compartments of the ecosystem. In a recent science article, Thompson *et al.* (2004) reported that plastic debris around the globe can erode (degrade) away and end up as microscopic granular- or fibre-like fragments, and that these fragments have been steadily accumulating in the oceans. Their experiments show that marine animals consume microscopic bits of plastic, as seen in the digestive tract of an amphipod. The Algalita Marine Research Foundation (see www.algalita.org/pelagic_plastic.html) reports that degraded plastic residues can attract and hold hydrophobic elements like polychlorinated biphenyls (PCB) and dichlorodiphenyltrichloroethane (DDT) up to 1 million times background levels. The PCBs and DDTs are at background levels in soil, and diluted out, so as to not pose significant risk. However, degradable plastic residues with these high surface areas concentrate these chemicals, resulting in a toxic legacy in a form that may pose risks in the environment. Japanese researchers (Mato *et al.* 2001) have similarly reported that PCBs, DDE and nonylphenols (NP) can be detected in high concentrations in degraded PP resin pellets collected from four Japanese coasts. This work indicates that plastic residues may act as a transport medium for toxic chemicals in the marine environment (see discussion in Teuten *et al.* 2009).

Therefore, designing hydrophobic polyolefin plastics like PE to be degradable, without ensuring that the degraded fragments are completely assimilated by the microbial populations in the disposal infrastructure in a short time period, has the potential to harm the environment more than if it was not made degradable. Heat, moisture, sunlight and/or enzymes can shorten and weaken polymer chains, resulting in fragmentation of the plastic and some cross-linking, creating more intractable persistent residues. It is possible to accelerate the breakdown of the plastics in a controlled fashion to generate these fragments, some of which could be microscopic and invisible to the naked eye, and some elegant chemistry has been done to make this happen as reported in the literature (Scott & Wiles 2001). However, this degradation/fragmentation is not biodegradation *per se* and these degraded, hydrophobic polymer fragments pose potential risks in the environment unless they are completely assimilated by the microbial populations present in the disposal system in a relatively short period.

(ii) *Measurement of biodegradability*

Micro-organisms use the carbon substrates to extract chemical energy that drives their life processes by aerobic oxidation of glucose and other readily usable C-substrates (Narayan 1994):

$$\text{C-substrate} + 6O_2 \rightarrow 6CO_2 + 6H_2O,$$

$$\Delta G_0 = -686\ \text{kcal/mol} \qquad (CH_2O)_x; \quad x = 6$$

Thus, a measure of the rate and amount of CO_2 evolved in the process is a direct measure of the amount and rate of microbial use (biodegradation) of the C-polymer. This forms the basis for various international standards for measuring biodegradability or microbial use of the test polymer/plastics. The rate and extent of biodegradation or microbial use of a test plastic material can be measured by using it as the sole added carbon source in a test system containing a microbially rich matrix-like compost in the presence of air, and under optimal temperature conditions (preferably at 58°C—representing the thermophilic phase). Figure 3 shows typical data obtained when the per cent carbon released (as CO_2) from a bioplastic exposed in a composting environment is plotted as a function of time. First, a lag phase occurs during which the microbial population adapts to the available test C-substrate. Then follows the biodegradation phase during which the adapted microbial population begins to use the carbon substrate for its cellular life processes, as measured by the conversion of the carbon in the test material to CO_2. Finally, the output reaches a plateau when use of the substrate is largely complete.

Based on the above concepts, the ASTM committee D20.96 on Biobased and Environmentally Degradable

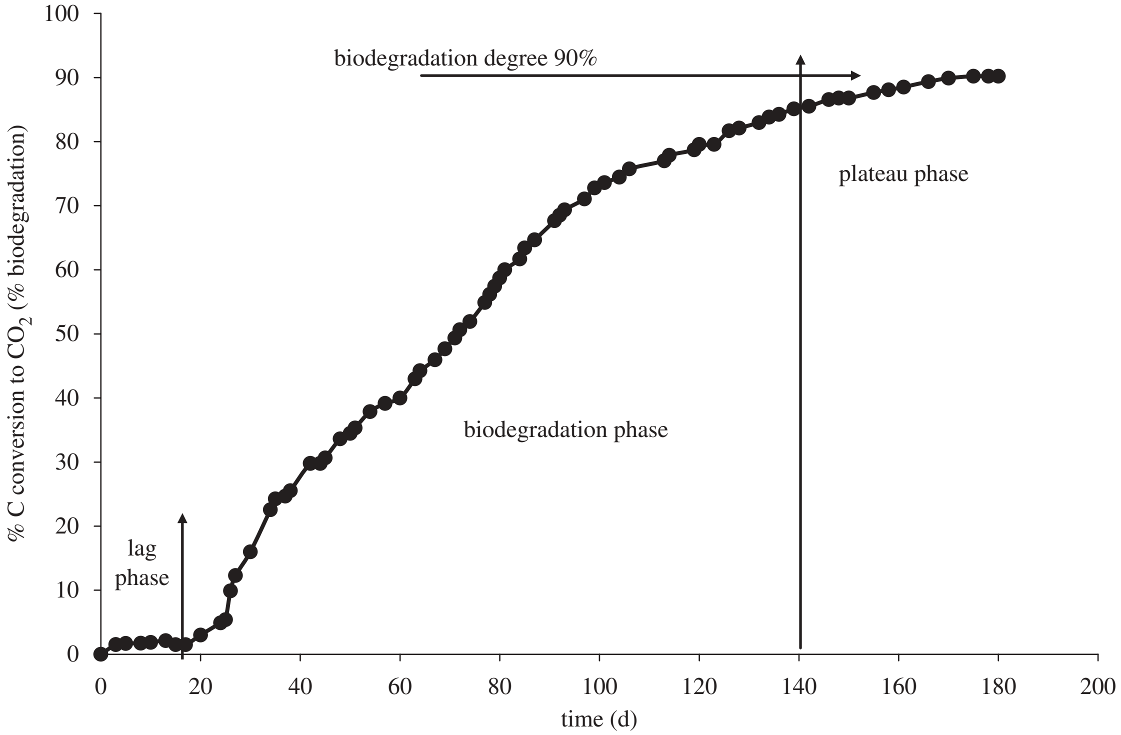

Figure 3. Example data from a biodegradation test of a biodegradable biopolymer assessed as CO_2 release over 180 days. CO_2 release curve shows typical lag phase, biodegradation phase and plateau phase.

Plastics (www.astm.org) developed a Specification Standard D6400 (see also D6868) for products claiming to be biodegradable under composting conditions or compostable plastics (ASTM, 2002). The above specification standard is in harmony with standards in Europe, Japan, Korea, China and Taiwan. EN13432 'Requirements for Packaging Recoverable through Composting and Biodegradation—Test Scheme and Evaluation Criteria for the Final Acceptance of Packaging' is the European standard (norm) and similar to D6400. The current UK standard BS EN 13432 (2000) covers the requirements for packaging recoverable through composting and biodegradation and test scheme and evaluation criteria for the final acceptance of packaging. At the international level, the International Standards Organization (ISO) has developed ISO 17088, 'Specification for Compostable Plastics' which is in harmony with these European and US norms.

The fundamental requirements of these worldwide standards for complete biodegradation under composting conditions are:

- (i) conversion to CO_2, water and biomass via microbial assimilation of the test polymer material in powder, film or granule form.
- (ii) Ninety per cent conversion of the carbon in the test polymer to CO_2. The 90 per cent level set for biodegradation in the test accounts for a ± 10 per cent statistical variability of the experimental measurement; in other words, there is an expectation for demonstration of a virtually complete biodegradation in the composting environment of the test.
- (iii) Same rate of biodegradation as natural materials—leaves, paper, grass and food scraps.
- (iv) Time—180 days or less (ASTM D6400 also has the requirement that if radiolabelled polymer is used and the radiolabelled evolved CO_2 is measured, then the time can be extended to 365 days).

Two further requirements are also of importance:

- (i) Disintegration: <10 per cent of test material mass retained by a 2 mm sieve using test polymer material in the shape and thickness identical to the product's final intended use—see ISO 16929 and ISO 20200.
- (ii) Safety: the resultant compost should have no impacts on plants, using OECD Guide 208, Terrestrial Plants, Growth Test or similar, such as PAS 100 (BSI 2002). Furthermore, regulated (heavy) metals content in the polymer material should be less than defined thresholds e.g. 50 per cent of EPA (USA and Canada) prescribed threshold.

(b) *Composting in practice*

The treatment of biodegradable plastics by composting is now considered in many parts of the world to be an appropriate form of material recovery. In the UK, it is a permitted recovery option specified in the Producer Responsibility (Packaging Waste) Regulations as amended in 1997.

In a large-scale study from March 2001, in Kassel, Germany, BDP packaging was introduced into the local retail trade (Klauss 2001). The purpose of this scheme was to introduce biodegradable packaging and manage its source separation by householders so that it could be collected with the organic waste stream to produce compost. The scheme required much planning prior to the launch, to ensure that the public had received sufficient information about the BDPs, their labelling, separation and collection. The mixed packaging and organic waste was composted at a full-scale composting site and was undertaken at a commercial level. The compost feedstock was monitored to ensure a relatively low proportion of one plastic to 99 parts organic waste on a weight basis. The compost produced showed no differences in terms of quality parameters compared with conventional compost comprising solely green waste (no BDPs) and had the same positive effects on soil and plant characteristics (Klauss & Bidlingmaier 2004).

Householder surveys indicated that 82 per cent of Kassel's population could clearly identify the logo printed on compostable polymers and 90 per cent supported the replacement of conventional plastic packaging with compostable packaging. The success of this programme has created a demand for further products that can be digested/degraded in the same way as 'conventional' organic waste. The benefits for this are twofold: (i) increased separation and collection efficiency (household or centralized) and (ii) reduced amount of waste to landfill or incineration.

Some legislation, however, imposes a number of constraints on the composting industry. In May 2003, the Animal By-Products Regulation (ABPR) started the UK implementation of an EU Regulation. The ABPR divides animal by-products into three categories and stipulates the means of collection, transport, storage, handling processing and use or disposal for each category: category 1, highest risk materials such as carcasses infected with BSE, scrapie, etc.; category 2, also high-risk materials such as animals that die on farms and animals that are unfit for human consumption; and category 3, materials that are fit (but not intended) for human consumption such as fish, milk, parts of slaughtered animals, etc. Household kitchen waste and, by association, biodegradable food packaging (because it has come into contact with food, meat or non-meat) are classified under Category 3. Categories 2 and 3 materials may be composted or treated via anaerobic digestion following strict requirements on handling, temperature and retention times.

Although the ABPR does not apply to sites accepting only green botanical garden waste, many UK Local Authorities have already started mixed organic waste (garden and kitchen) collections or are considering mixed collections in order to meet legislative targets. For mixed organic waste collections, the majority of the material collected is from botanical sources; however, due to the presence of kitchen/catering waste all the waste must be composted in-vessel in order to meet the requirements. Local Authorities could collect the organic botanical waste separately from the kitchen-derived waste, but this has extensive logistical and cost issues (separate vehicles, crew and composting facility). In-vessel composting is more costly than the open-windrow methods commonly adopted in the UK for pure 'green waste'. This results in increased composting costs per tonne, gate fees charged to Local Authorities and reduction in the competitiveness of in-vessel composting against other treatment and disposal options such as landfill.

Concerns over the potential ecotoxicity of degradation products have resulted in the formulation and adoption of suitable international standards for compostable polymer products. For example, EN 13432 requires that compostable polymer materials have to fulfill European, or where none exist, national requirements for compostability. In December 2003, the Composting Association in the UK launched a Certification Scheme for Compostable Packaging in order to assist UK Local Authorities with the selection of sacks for organic waste collections. As there is currently no European standard on compost quality (besides the ecological criteria for the award of the EU Eco-label), the UK adopted the BSI PAS 100 in November 2002 (BSI 2002). Other standards such as the ASTM D6400 and ISO 17088 also define product classification and requirements for composts.

(c) *Home (domestic) composting*

In the UK, home composting has been identified by the Strategy Unit of the Cabinet Office as one of five key measures to reduce the growth rate of household waste (Anon. 2002; Murphy & Bartle 2004). In addition to kitchen and garden waste, home composting of biodegradable packaging materials could divert waste from municipal collection systems and complement industrial composting. It must be noted that it is difficult to regulate home composting, and anaerobic composting conditions occurring in poorly managed systems will result in the generation of methane. Moreover, home composting using compost bins or heaps is more variable and less optimized than industrial composting and the temperature achieved is rarely more than a few °C above ambient temperature. Under such conditions, certain compostable materials certified for industrial composting (EN13432) may not biodegrade sufficiently. The 'OK Compost Home' standard, which repeats the EN13432 test protocol at ambient temperature, as shown in table 1, has been established by AIB-VINÇOTTE in Brussels (www.aib-vincotte.com). These temperature conditions do not reflect true composting process principles which require them, by definition, to go through a thermophilic phase (55–65°C) that can last from a few days to a couple of months depending on the composting volume. The thermophilic phase of composting is of importance to ensure the destruction of thermosensitive human and plant pathogens, fly larvae and weed seeds. Regulations by the US Environmental Protection Agency specify that to achieve a significant reduction of pathogens during composting, the compost should be maintained at minimum operating conditions of 40°C for 5 days, with temperatures exceeding 55°C for at least 4 h of this period.

Some bioplastic polymers, particularly used as bags and pots for horticulture or waste collection bag applications, have been certified by the OK Compost Home scheme while others passed only 'OK Compost' standard for industrial composting (http://www.aib-vincotte.com/data) and are not suitable for home

Table 1. Comparison of standards for industrial and home composting.

	industrial composting (EN 13432)	home composting (vincotte certification)
biodegradation	test at 58°C in 180 days biodegradation min. 90%	test at 20–30°C in 365 days biodegradation min. 90%
disintegration	test at 58°C in 90 days sieve 2 mm mesh disintegration >90% max. 10% of dry weight allowed to be retained by 2 mm sieve	test at 20–30°C in 180 days sieve 2 mm mesh disintegration >90% max. 10% of dry weight allowed to be retained by 2 mm sieve
certification	Din Certco/OK Compost	OK Home

composting. This distinction is important and it is vital that clear guidance is communicated to the public who may otherwise assume that any products labelled as ‘biodegradable’, ‘compostable’ or ‘eco-’ under the numerous certification systems can simply be put into their home or garden compost bins. These are unlikely to reach the thermophilic compost temperatures required for both suitable degradation of certain materials and to achieve sanitization.

New research to characterize the extent of biodegradation when a range of biodegradable or potentially biodegradable packaging materials are disposed of in simulated home composting typical of the UK is presented briefly below. The objective was to establish whether potentially biodegradable packaging materials would show appropriate levels of biodegradation when exposed to ‘typical’ home compost conditions (non-thermophilic) together with green garden waste. Small specimens of 12 bio-based materials (six were from materials used commercially and six were from developmental materials that were designed to be biodegradable—see table 2) were assessed as material weight loss over a 24-week winter/spring period between November and May in the southeast of the UK. Whole food packaging units (trays/plate) made from three of the materials were also assessed under the same conditions but were mixed directly into the compost matrix.

The composting was undertaken outdoors in the home-composter, lidded ‘cone’ systems (volume 160 l) filled with a ‘base mixture’ of approximately 60 per cent green herbaceous and grass clippings and 40 per cent chopped ‘woody’ herbaceous material from the local site that was free of pesticides or herbicides and had previously been composted for 30 days to establish an active microflora/fauna. Twelve packaging materials (approx. 25 × 25 mm sheets) were individually secured into nylon mesh bags and replicate specimens placed into a stainless steel rack for easy retrieval. The sample racks were inserted in the middle of a composting bin between layers of base mixture (approx. 600 mm below the compost mixture surface). Three replicate composter units were established with three replicate specimens of each material removed per composter per sampling time. Additional six composter bins were set up, two of each with 6.4 wt% of one of the three main packaging materials (potato starch trays, PLA trays and paper plate) as whole units mixed in with the green waste base mixture. Two further composter bins containing only the compost base mix and no added biodegradable packaging materials were used as controls for a subsequent seed germination comparison.

The composters were sampled on a monthly basis from November to May for determination of specimen mass loss and MC (od basis), temperature and overall compost volume reduction. Replicate samples of the small test materials or whole units were removed at each sampling interval. ‘Turning’ of the composts was done only on these occasions.

A bioassay of the composts from the whole packaging unit test and the control compost was also conducted in accordance with the ‘Specification for composted materials’ (PAS 100; BSI 2002). F1 tomato seeds (variety Shirley, Sutton Seeds, UK) were placed in the prescribed mixture of a peat-based growth medium (PBGM) and test compost (1 : 2 ratio by volume of compost to PBGM base mix) in seed trays and maintained with regular watering at a temperature of 20–25°C in a natural light greenhouse in early summer 2005 over a 28-day period of the test. Seed germination, fresh plant mass, abnormalities and weed emergence were recorded in accordance with PAS 100.

The compost bin systems functioned as a low temperature composting environment between 15°C and 18°C in November at the start of the experiment. The temperature dropped to a low of approximately 8–10°C in January/February/March and then rose again to approximately 14°C in May. The composter bin temperatures were considerably lower than specified (20–30°C) in the OK Compost Home standard (table 1) but reflect the typical seasonal temperatures in the southeast of the UK. All composter bins showed an acceptable level of reduction in biomass volume (approx. 50%) during the composting period. The temperature profiles of the bins and the degradation of their contents were largely consistent across the whole study.

Table 2. Packaging materials used for simulated home composting. (Fast degrader = mass loss approximately 80% after 90 days; medium degrader = mass loss approximately 40% after 90 days; slow degrader = mass loss <5% after 90 days.)

name	commercial (C)/ experimental (E) material	material	principal components (wt%)	small sample	whole unit	rate of degradation
potato starch	C	potato starch-based tray	potato starch (<75%)	✓	✓	fast
starch laminate	C	starch-based tray with a starch/PCL laminate	starch; starch PCL surface overlay	✓		fast
paper	C	pressed wood pulp plate	wood pulp 70%; starch size 20%; other 10%	✓	✓	medium
silvergrass	C	pressed silvergrass pulp plate	*Miscanthus* spp. pulp	✓		fast
coconut	C	moulded coconut fibre tray	*Cocos nucifera* fibre	✓		medium
recycled paper	C	moulded recycled paper pulp tray	recycled paper	✓		medium
PLA	E	PLA tray	100% PLA	✓	✓	slow
starch/PCL	E	starch/PCL—extrudate sample	100% starch/PCL	✓		slow
PP(A)	E	PP with biodegradability additive A	90% PP; 10% bio-additive A	✓		slow
PP(B)	E	PP with biodegradability additive B	90% PP; 10% bio-additive B	✓		slow
PP(B)+	E	PP with biodegradability additive B plus chalk filler	60% PP; 10% bio-additive B; 30% chalk	✓		slow
PP/starch	E	PP compounded with starch granules	88% PP; 10% starch granules; 2% other	✓		slow

The visual assessment showed that complete disintegration and incorporation of the starch trays into the compost matrix had occurred after 90 days of composting. The paper-plate material was also extensively broken down over the composting period, although it was possible to distinguish elements of the original plate material after 180 days, despite their being heavily discoloured and lacking structural integrity. The PLA polymer showed no visual evidence of microbial breakdown after 180 days, although some fragments had broken off from the trays. This was not considered to be disintegration as a result of biodegradation but was attributed to disturbance of the bins and mechanical damage when retrieving samples.

The mass loss (as an indicator of the biodegradation) data for the full range of material types as small specimens are presented in figure 4 and for the whole units in figure 5. From approximately 90 days exposure, three groups of materials could be clearly distinguished:

- (i) The fast degraders (starch-based polymers and the plant fibre-base silvergrass) exhibiting mass losses of approximately 80 per cent.
- (ii) The medium degraders (wood fibre-based paper and the coconut fibre) with mass losses of approximately 40 per cent.
- (iii) The slow degraders (PLA, PP with additives and starch/PCL) with negligible mass loss <5 per cent.

This differentiation of the three groups was then maintained to the conclusion of the experiment at 180 days (table 2). The fast degraders lost approximately 90 wt% and became visually indistinguishable from their sealed packets; the medium degraders lost approximately 50 wt% and remained recognizable on close inspection. The slow degraders lost typically less than 5 wt% and were clearly recognizable.

The results for MC assessment showed that fast and medium degraders absorbed moisture readily during the composting process, typically ranging from 100 to 300 per cent for the starch and fibre materials over the 30- to 180-day period. The slow degrader group exhibited very low levels of moisture absorption with the starch/PCL, PP/starch and PLA typically below 10 per cent and the PP/modifiers below 1 per cent.

The results of the PAS 100 bioassay (data not shown) showed that composts derived from the composters containing whole packaging units (starch, paper and PLA) and from the controls gave equal or higher seed germination rates and equivalent or better fresh seedling weights compared with the growth medium base alone (an exception was one PLA compost bin that had a 21 per cent reduction in seedling fresh weight). All the amended composts failed the weed criterion of PAS 100, but this is expected because low-temperature composting systems do not achieve sterilization of weed seeds.

This study has shown that biodegradable packaging materials exhibited a wide range of biodegradation properties in this simulated home composting system run under non-thermophilic conditions (a regime where mesophilic micro-organisms dominate). It is clear that this mesophilic home composting condition may be less favourable for biodegradation than those specified in some standards. For instance, the home composting system used in this study operated over a temperature range of approximately 5–18°C rather than the 20–30°C range specified in the OK

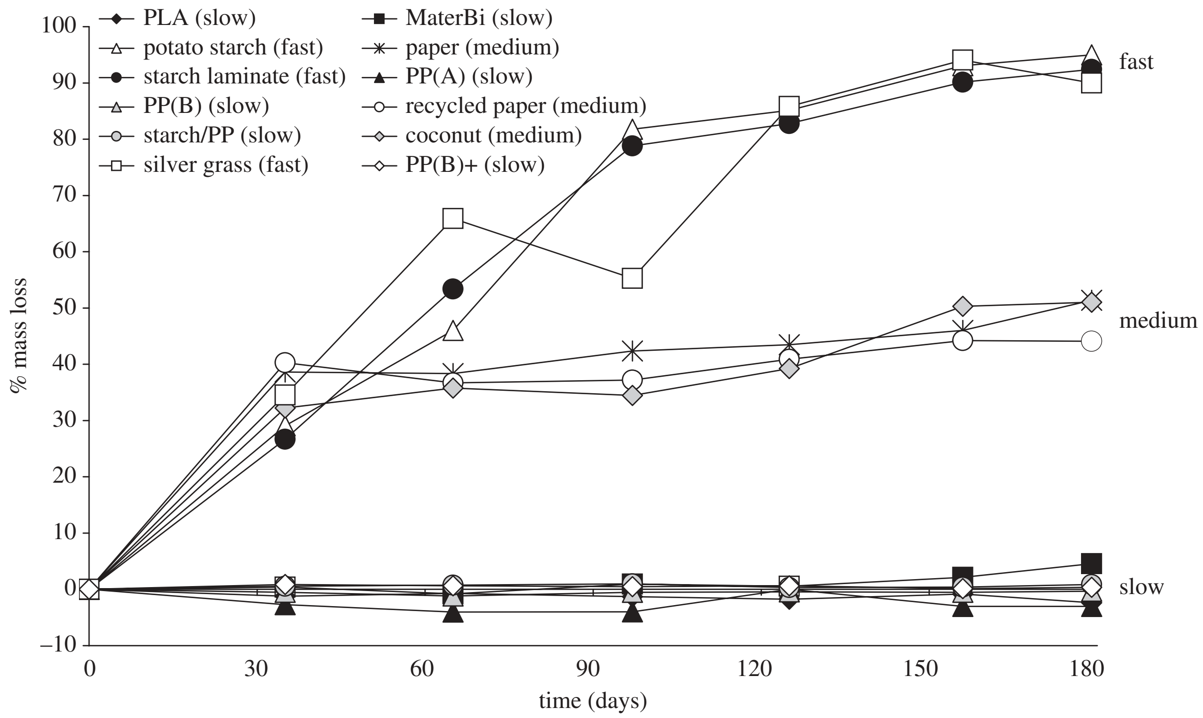

Figure 4. Mass loss (wt%) over time—test materials as small samples (Note: PLA, potato starch and paper are also represented as whole packaging units in figure 5) (error bars not shown for clarity, 95% confidence interval ranged between 1% and 20% mass loss). ‘Fast’, ‘medium’ and ‘slow’ refer to rates of degradation indicated in table 2.

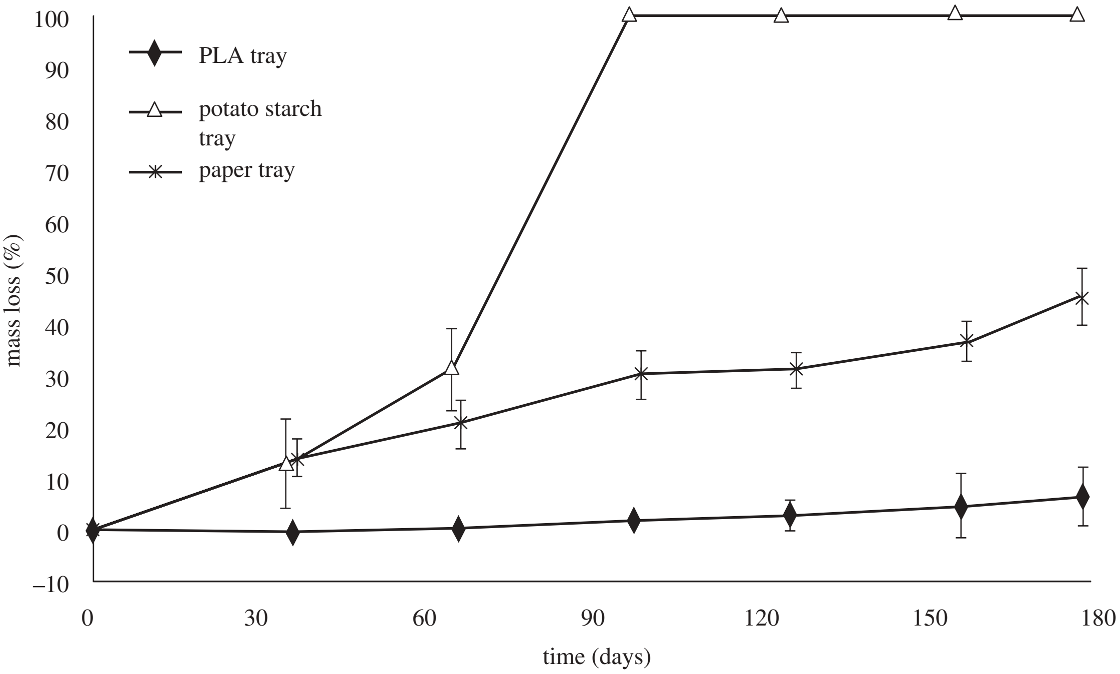

Figure 5. Mass loss (wt%) over time—whole packaging units (Note: PLA tray, potato starch tray and paper plate are also represented as small samples in figure 4) (error bars are 95% confidence intervals).

Compost Home standard. The fast degrader bioplastics, predominantly based on high levels of starch and the grass fibre/starch composite, were readily biodegraded in the home composting system. The medium degraders based on wood or coconut fibres exhibited mass losses of approximately 50 per cent over the composting period. The easily fragmentable nature of the residual material at the end of the 180-day period enabled the medium degraders to be readily incorporated into the compost matrix and we conclude that medium degraders would be acceptable in terms of disintegration. The extent of biodegradation of these materials, however, failed to satisfy the >90 per cent requirement within 180 days of BS EN 13432. How this may change should the test be extended to 360 days (as in the OK Compost Home standard) and whether this can be mitigated (as for cellulose residues in farm compost) remain to be studied further. The slow degraders (e.g. combined starch/biodegradable polyester formulation and PLA), including bioplastic polymers certified as compostable under EN 13432 conditions, exhibited either no or very low levels of biodegradation and fragmentation over the composting period. Although greater degradation may be achieved over longer periods (e.g. expansion to 360 days), elevated temperature around 60°C has been shown to be a crucial parameter, enabling the induction of biodegradation of polymers such as PLA (e.g. Agarwal *et al.* 1998; Scott & Wiles 2001; Tokiwa & Jarerat 2004). Such temperatures are clearly lacking in home composting systems of the type modelled. The seed germination study indicated that composts made from green waste incorporating approximately 6 per cent by mass of home composted starch or paper trays give growth media that support good seed germination and seedling development. Although similar results were also achieved with compost incorporating non-biodegraded PLA materials, it must be noted that the compost with PLA trays would fail the disintegration requirements set in the OK Compost Home as the PLA trays remained almost intact. Inhibition of seedling development, in composts with degradable PE and control composts from open-window systems, has been found by Davis *et al.* (2005).

It is clear from this research that several biodegradable packaging materials can be processed in home composting systems and yield compost materials suitable for plant growth. This capability will enable such materials to be disposed of in well-run home composting systems and result in waste diversion from municipal waste streams. However, we have also demonstrated that a number of packaging materials that typically biodegrade well in industrial, thermophilic high-temperature composting systems failed to biodegrade adequately in home composting environments that operate as low temperature, mesophilic environments.

At a practical level, these results suggest that it is vital to clearly distinguish biodegradable packaging materials that can be expected to biodegrade under ambient, mesophilic conditions typically found in UK home composting systems from those that biodegrade under the complete thermophilic–mesophilic (55–65°C) regime of an industrial composting systems. Labelling schemes and consumer education and information should support such a distinction.

5. CONCLUDING REMARKS

Biodegradable polymers will play a greater role in the packaging sector in the future. Post-use biodegradable plastics and other biowastes like paper, food and garden waste are generally unsuitable for landfill due to their potential to release methane under anaerobic conditions and their disposal by this method is inconsistent with policies like the EU Landfill Directive. Biodegradable bioplastics are most suitable for biological waste treatment through industrial and/or domestic composting and, subject to further demonstration, potentially in anaerobic digestion systems. They should ideally be separated at the household level from other, non-biodegradable materials and collected with organic waste, including food waste. By using these biological treatment methods, the total quantities of waste sent to landfill are reduced and the composts generated can be used as valuable soil improvers.

Implementing effective biological treatments for the developing range of biodegradable bioplastics requires the support of clear certification and labelling schemes. Biodegradable plastics that pass the relevant compostability standards will biodegrade well in industrial composting systems. However, as discussed, only some of those plastics will also biodegrade adequately under ambient, mesophilic regimes typical of UK home composters, and this distinction needs to be communicated effectively to the wider public (see Thompson *et al.* 2009*b*).

Bioplastic polymers have great potential to contribute to material recovery, reduction of landfill and use of renewable resources. Widespread public awareness of these materials and effective infrastructure for stringent control of certification, collection, separation and composting will be crucial to obtaining these benefits in full.

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Appendix 5 -- Degradable vs complete microbial utilization (biodegradable) – excerpted from *Phil. Trans. R. Soc. B* 2009 **364**, 2127-2139, in Appendix 4)

A number of polymers in the market place are designed to be degradable, i.e. they fragment into smaller pieces and may even degrade to residues invisible to the naked eye. While it is assumed that the breakdown products will eventually biodegrade, there are no data to document complete biodegradability within a reasonably short time period (one year or less; the FTC time period). Hence hydrophobic, high surface area plastic residues may migrate into water and other compartments of the ecosystem. In a recent science article, Thompson et al. (2004) reported that plastic debris around the globe can erode (degrade) away and end up as microscopic granular- or fibre-like fragments, and that these fragments have been steadily accumulating in the oceans. Their experiments show that marine animals consume microscopic bits of plastic, as seen in the digestive tract of an amphipod. The Algalita Marine Research Foundation (see www.algalita.org/pelagic_plastic.html) reports that degraded plastic residues can attract and hold hydrophobic elements like polychlorinated biphenyls (PCB) and dichlorodiphenyltrichloroethane (DDT) up to 1 million times background levels. The PCBs and DDTs are at background levels in soil, and diluted out, so as to not pose significant risk. However, degradable plastic residues with these high surface areas concentrate these chemicals, resulting in a toxic legacy in a form that may pose risks in the environment. Japanese researchers (Mato et al. 2001) have similarly reported that PCBs, DDE and nonylphenols (NP) can be detected in high concentrations in degraded PP resin pellets collected from four Japanese coasts. This work indicates that plastic residues may act as a transport medium for toxic chemicals in the marine environment (see discussion in Teuten et al. 2009).

Therefore, designing hydrophobic polyolefin plastics like PE or compostable products to be degradable, without ensuring that the degraded fragments are completely assimilated by the microbial populations in the disposal infrastructure in a short time period, has the potential to harm the environment more than if it was not made degradable. Heat, moisture, sunlight and/or enzymes can shorten and weaken polymer chains, resulting in fragmentation of the plastic and some cross-linking, creating more intractable persistent residues. It is possible to accelerate the breakdown of the plastics in a controlled fashion to generate these fragments, some of which could be microscopic and invisible to the naked eye, and some elegant chemistry has been done tomake this happen as reported in the literature (Scott & Wiles 2001). However, this degradation/fragmentation is not biodegradation per se and these degraded, hydrophobic polymer fragments pose potential risks in the environment unless they are completely assimilated by the microbial populations present in the disposal system in a relatively short period.

For the cited references see Appendix 4 paper.

ASTM STANDARDS HELP DEFINE AND GROW A NEW BIODEGRADABLE PLASTICS INDUSTRY

This paper was submitted to the ASTM Impact of Standards Paper Contest, part of ASTM's centennial commemorations in 1998. Throughout this year, meritorious papers such as this one have been published. The winning papers were presented in the Feb. 1999 issue of SN.

by Ramani Narayan

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by Charles A. Pettigrew

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Introduction

For 100 years ASTM has provided the mechanism by which industry, government, and academia come together to develop consensus standards. Through these standards, industry and governments (and their regulatory agencies) can operate in a clear, safe, and effective manner for the benefit of the general public. The ASTM process has continuously evolved over these 100 years to provide state-of-the-art, scientifically credible standards that are used throughout the world. It was, therefore, inevitable that when industry introduced degradable and recycled plastics in response to the new environmental and sustainable development drivers, they turned to ASTM to help set the standards in this area.

In this paper, we showcase the important role ASTM standards played in helping define and grow a new biodegradable plastics industry. The standards helped overcome the confusion and misunderstandings in this new area. They provided a level, well-defined field whereby companies could introduce new degradable products, governmental agencies could monitor and confirm degradability claims, and consumers could safely use and dispose of the products with a clear understanding of the environmental benefits of degradable products. This paper also demonstrates the synergistic value and utility of ASTM's Institute for Standards Research (ISR) in helping perform the necessary R&D to write standards in emerging technology areas such as degradable plastics.

Background

Emerging societal concerns and a growing environmental awareness throughout the world triggered the search for new materials and processes that enhance the environmental quality of products. Companies throughout the world have or are initiating the design and engineering of new products with holistic environmental evaluations beginning with the acquisition of raw materials, continuing through product use/reuse, and ending with disposal. Sustainable development and eco-efficiency are terms that have the attention of major international companies. In this context, biodegradability and recyclability have become important considerations in the design of new products.

Designing biodegradable polymer alternatives and ensuring that they end up in an appropriate disposal system can enhance the environmental quality of many products. For example, composting is an environmentally sound approach that recycles biodegradable waste into useful products and minimizes the amount of waste disposed in landfills. Composting biodegradable polymers and paper waste along with other compostable materials like yard, food, and agricultural wastes generates high quality soil amendment products. Compost amended soil creates the beneficial effects of increasing soil organic carbon, increasing water and nutrient retention, reducing chemical inputs, and suppressing plant disease. The composting infrastructure, which is a key consideration in the ultimate disposal of biodegradable polymers, is growing in North America and Europe. In the United States, close to 3,000 facilities compost yard waste, about 150 compost sludge, 30 compost food and food processing waste, and 20 compost mixed waste. In particular, yard waste composting facilities have shown dramatic growth; since 1988 an average of 470 new yard waste composting facilities have opened each year. Figure 1 (next page) conceptually shows a cradle-to-grave closed loop of design, use, disposal, and re-use of annually renewable resources.

Another major area of concern is marine plastics (single-use disposable plastics used in ships, plastic fishing nets and other similar items). The International MARPOL treaty (the U.S. is a signatory to the treaty along with other large and small countries) prohibits the dumping of non-degradable plastics in the sea, but degradable plastics that have the degradability attributes of paper could be an acceptable proposition. For example, plastic ring connectors that hold cans and bottles were causing the deaths of marine animals which resulted in U.S. Public Law 100-56. U.S. Public Law 100-56 requires degradable ring carriers for bottles and cans.

Table 1. Environmentally Degradable Plastics Standards

COMPOSTING ENVIRONMENT

1. Standard Test Method for Determining the Aerobic Biodegradation of Plastic Materials in the Presence of Municipal Sewage Sludge [D 5209]
2. Standard Test Method for Determining the Aerobic Biodegradation of Plastic Materials Under Controlled Composting Conditions [D 5338]
3. Standard Practice for Exposing Plastics to a Simulated Compost Environment [D 5509]
4. Standard Practice for Exposing Plastics to a Simulated Compost Environment Using an Externally Heated Reactor [D 5512]
5. Standard Test Method for Determining Weight Loss from Plastic Materials Exposed to a Simulated Municipal Solid Waste (MSW) Aerobic Compost Environment [D 6003]
6. Standard Test Method for Determining the Aerobic Biodegradation in Soil of Plastic Materials or Residual Plastic Materials After Composting [D 5988]
7. Guide to Assess the Compostability of Environmentally Degradable Plastics [D 6002]—ISR Program
8. Standard Test Method for Determining Weight Loss from Plastic Materials Exposed to a Simulated Municipal Solid-Waste (MSW) Aerobic Compost Environment [D 6003]
9. Standard Test for Determining Aerobic Biodegradation of Radiolabeled Plastic Materials in Compost Environment [D 6340]—ISR Program
10. Standard Test Method for Determining Aerobic Degradation of Plastic Materials in a Full Scale Composting Environment [New Standard, in Committee Ballot]—ISR Program
11. Specifications for Compostable Plastics [D 6400]—ISR Program
12. Standard Practice for Preparing Residual Solids Obtained After Biodegradability Standard Methods for Toxicity and Compost Quality Testing [D 5951]—Fate & Effect Testing
13. Standard Practice for Water Extraction of Residual Solids from Degraded Plastics for Toxicity Testing [D 5152]—Fate & Effect Testing

ANAEROBIC DIGESTION / PROCESSES

14. Standard Test Method for Determining the Aerobic Biodegradation of Plastic Materials or Residual Plastic Materials After Composting in Contact with Soil [D 5988]
15. Standard Test Method for Assessing the Aerobic Biodegradation of Plastic Materials in an Activated-Sludge-Wastewater-Treatment System [D 5271]
16. Standard Test Method for Determining the Anaerobic Biodegradation of Plastic Materials in the Presence of Municipal Sewage Sludge [D 5210]
17. Standard Test Method for Determining Anaerobic Biodegradation of Plastic Materials Under High-Solids Anaerobic Digestion Conditions [D 5511]
18. Standard Test Method for Determining Anaerobic Biodegradation of Plastic Materials Under Accelerated Landfill Conditions [D 5526]
19. Standard Practice for Exposing Plastics To a Simulated Landfill Environment [D 5525]

OTHER

20. Standard Practice for Weathering of Plastics Under Marine Floating Exposure [D 5437]
21. Standard Test Method for Determining the Aerobic Biodegradability of Degradable Plastics By Specific Microorganisms [D 5247]
22. Standard Practice for Heat Aging of Oxidatively Degradable Plastics [D 5510]
23. Standard Test Method for Determining Hydrolytic Degradation of Plastic Materials in an Aqueous Solution [D 6118]

PHOTODEGRADATION ENVIRONMENT

24. Practice for Determining Degradation End Point in Degradable Polyolefins Using a Tensile Test [D 3826]
25. Practice for Operating Xenon Arc-Type Exposure Apparatus with Water for Exposure of Photodegradable Plastics [D 5071]
26. Practice for Operating Fluorescent UV and Condensation Apparatus for Exposure of Photodegradable Plastics [D 5208]

A Challenge/Opportunity

As the industry began implementing approaches to design biodegradable materials and products, questions about the practicality, efficacy, and the effects of such products on the environment were raised. The U.S. Federal Trade Commission (FTC), a group of state attorneys general, state legislatures, and the U.S. Congress became very concerned about the various degradability and environmental claims being made, especially as they related to existing waste management practices. Verification of degradability claims and environmental fate and effects of the new degradable products using acceptable well-defined testing protocols were lacking.

The plastics industry failed to take advantage of this opportunity at the beginning by introducing starch filled (6 to 15 percent) polyolefins that were claimed to be biodegradable materials. At best, these materials only disintegrated and did not completely biodegrade. The introduction of these materials resulted in a number of regulatory actions. Eleven states enacted environmental marketing claim laws. A task force of several state attorneys general issued recommendations (Green Report I and II) on advertising related to products and environmental attributes. Between October 1990 and June 1992, 48 separate actions were taken for misleading or deceitful environmental advertising; the highest number of actions were on claims of biodegradable plastics, and the use of the terms biodegradable and recyclable.

Thus, it became increasingly clear that standard test methods and protocols were sorely needed to establish and quantify the degradability and biodegradability of polymers, and to confirm the benign nature of the breakdown products. In order to ensure societal, regulatory, and market acceptance of biodegradable polymers, the ultimate biodegradability of these materials needed to be demonstrated in appropriate waste management infrastructures (like composting where biodegradation can occur). Federal and state governments looked to their Environmental Protection Agencies to set the standards to regulate this nascent industry. The EPAs, in turn, looked to industry to provide well-defined standards and measurements that could be used to regulate the industry.

Standards Development for Environmentally Degradable Plastics

It was in this confused and vexing regulatory climate that ASTM Committee D-20 on Plastics undertook the development of standards in the area of degradable plastics. ASTM's proven, century old, voluntary consensus process involving a balanced participation of government, industry, and academia was well suited to bring order and understanding in this new area.

Committee D-20 formed Subcommittee

Figure 1.

Sustainable Design, Use, Disposal, and Reuse of Resources

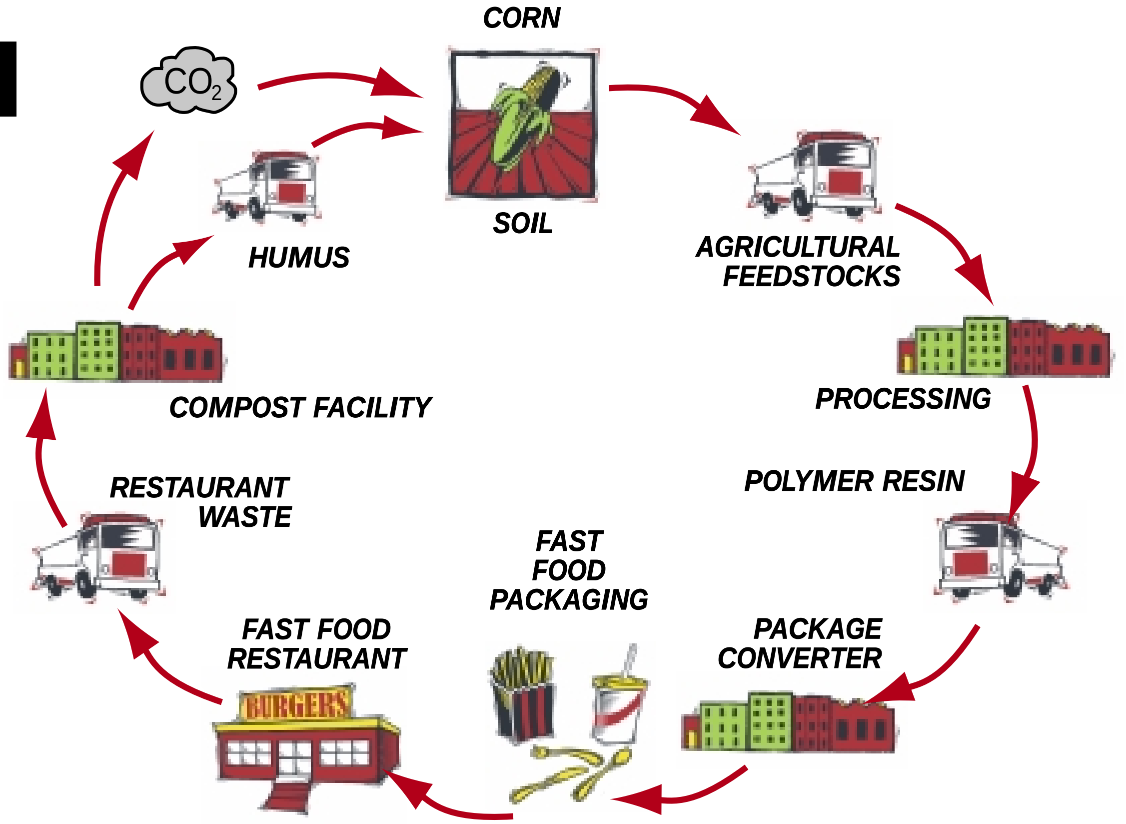


Table 2. ASTM & ISO Definitions on Environmentally Degradable Plastics

degradable plastic, n—a plastic designed to undergo a significant change in its chemical structure under specific environmental conditions resulting in a loss of some properties that may vary as measured by standard test methods appropriate to the plastic and the application in a period of time that determines its classification.

biodegradable plastic, n—a degradable plastic in which the degradation results from the action of naturally-occurring micro-organisms such as bacteria, fungi and algae.

photodegradable plastic, n—a degradable plastic in which the degradation results from the action of natural daylight.

oxidatively degradable plastic, n—a degradable plastic in which the degradation results from oxidation.

hydrolytically degradable plastic, n—a degradable plastic in which the degradation results from hydrolysis.

compostable plastic, n—a plastic that undergoes degradation by biological processes during composting to yield carbon dioxide, water, inorganic compounds, and biomass at a rate consistent with other known, compostable materials and leaves no visually distinguishable or toxic residue.

D20.96 on Environmentally Degradable Plastics to address the issue of standards for degradable polymers. The scope of the subcommittee was the promotion of knowledge, and the development of standards (classifications, guides, practices, test methods, terminologies, and specifications) for plastics that are intended to environmentally degrade. Over 170 members representing a broad spectrum of interests ranging from producers, converters, users, consumers, and general interest joined the subcommittee. Industry, government, academia, and national laboratories were represented on the subcommittee. Interestingly, the large majority of the members joining were new to ASTM and its consensus process. Thus the ASTM process was, once again, called upon to provide the framework to bring order and understanding in the form of standards to yet another emerging industry.

Recognizing the complexity and diversity of the standards development activity in this area, a modular standards development protocol was adopted. This is exemplified in Figure 2 (next page) and addresses:

- The environment to which plastic will be exposed (simulating a real-world disposal system or environment);
- The test method to ensure degradability (mechanical and chemical property loss) and biodegradability (microbial assimilation/degradation);
- The fate and effects of the degraded products; and
- Classification based on intended application.

The subcommittee is divided into sections to address these and other aspects of degradability. the sections under D20.96 are:

- Biodegradable (D20.96.01);
- Photodegradable (D20.96.02);
- Chemically degradable—hydrolytic and oxidative (D20.96.03);
- Environmental fate (D20.96.04);
- Terminology (D20.96.05); and
- Classification and marking (D20.96.06).

Using the protocol described in Figure 2 (next page), the subcommittee has, to date, 26 approved standards on the books. These standards cover various photo and bio environments that plastics may be exposed to, and methods to quantify the degradability. Table 1 (page 37) lists the developed standards. Table 2 (above) lists the definitions crafted by the subcommittee. These definitions are now International Organization for Standardization (ISO) standards as well. The standards measure biodegradability under different environmental/disposal conditions including composting, soil, marine, wastewater treatment, and anaerobic digestion. The original standards activity was started in ASTM with CEN (European Committee for Standardization), DIN (Deutsches Institut für Normung), and ISO standards closely following the ASTM standards with only minor variations. The majority of the standards address the composting disposal environment, given the importance of composting as an ecologically sound disposal method that generates useful soil amendment products, important for sustainable agricultural practices.

ASTM Institute for Standards Research Degradable Polymers Research Program

As Subcommittee D20.96 started writing standards in this new degradable polymers area, it became increasingly clear that a certain amount of research needed to be conducted before good credible standards could be written. Through the ASTM Institute for Standards Research, Subcommittee D20.96 instituted the Degradable Polymers Research Program to provide the basis for scientific substantiation of disposability statements for degradable polymeric materials in full scale disposal systems. The goal was to determine the behavior of degradable polymeric materials in real disposal systems, and how that correlates with ASTM and other laboratory tests in order to assure that such materials are safe for disposal and effectively degraded. A more important goal was to write standards based on the results of the research conducted. Composting was selected as the first disposal/waste management system for study. As discussed earlier, composting is an important waste disposal option. Furthermore, the Federal Trade Commission (FTC) and state attorneys general found the greatest number of problems were with compostability claims.

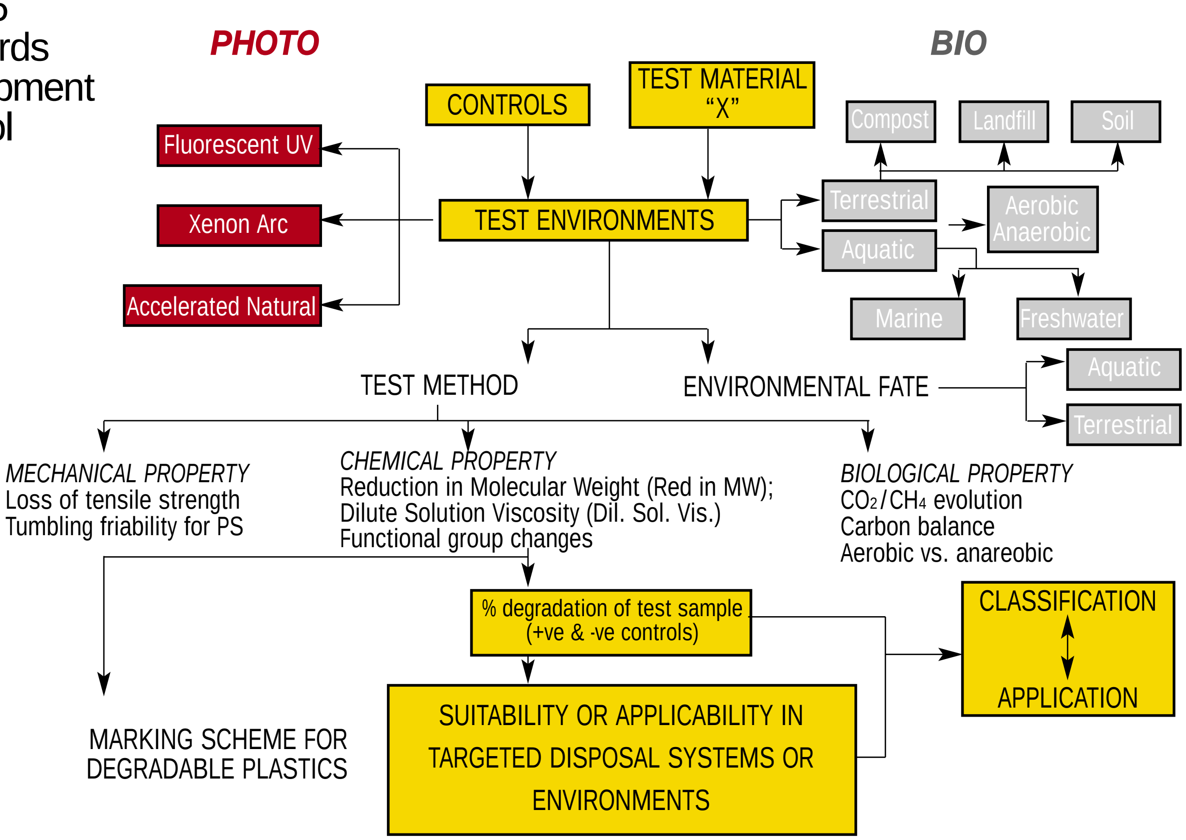
The Degradable Polymers Research Program was funded by industry, including some large multinational companies, government agencies, and trade/consumer organizations as shown in Table 3 (next page). This testifies to the importance of this new environmentally degradable polymer materials area. It is also testimony to the vision and creativity of ASTM in making ISR a forum that facilitates such diverse interests to come together and conduct R&D that would help in writing good, technically sound standards.

Experimentally determining the fate of a polymeric material during composting involved determining first the physical and chemical stability of the materials and second, whether the materials had the potential to be completely biodegraded. This process started with screening level evaluations that were followed by confirmatory studies conducted in pilot, and full-scale composting systems. Similar approaches were used to understand the fate of a material in compost amended soil. In both cases there was a need to determine if persistent residues or intermediates were produced. In order to generate these data, the Advisory Committee on Degradable Polymers Program (ACDP) (see Table 3, next page) and ASTM Subcommittee D20.96 developed a tiered testing strategy for assessing the compostability of polymeric materials.

The ACDP tested a broad range of degradable materials, including synthetic materials and polymers derived from natural resources using the tiered testing strategy, including laboratory-, pilot-, and full-scale studies. The quantitative data generated in these studies formed the basis for the recommendations that the ACDP provided to the degradable polymer industry. These recommendations focused on the usefulness of the tiered testing strategy, drawing upon the results with specific polymeric materials as case studies. The ACDP, in conjunction with the ASTM Subcommittee D20.96 prepared standard D 6002, Guide to Assess the Compostability of Environmentally Degradable Plastics. This guide provides a systematic approach to determining the compostability of a plastic or any other material that could enter the municipal solid waste stream. The scheme is cost effective because information is generated from lower-level, less expensive tests to higher-level, more expensive ones. The strategy covers the three aspects of compostability: biodegradability, ecotoxicity, and composting processability (the mechanical behavior of the material in a compost process). A detailed report on the composting trial has been issued. Several other important test methods like the testing with radiolabeled materials, test methods for performing pilot and full-scale

FIGURE 2.

D20.96 Standards Development Protocol



composting, and specifications for compostable plastics evolved from the program, and are under various stages of balloting.

Impact of the Environmentally Degradable Plastic Standards

The technical standards, definitions, and test methods that have emerged from the ASTM and ACDP biodegradable polymer programs have had important commercial and societal impacts. As discussed earlier, the biodegradable polymer industry suffered a severe setback a decade ago when the first generation polyolefin-starch materials did not degrade as claimed. Through the seminal work and technical leadership of ASTM Subcommittee D20.96 and its ISR-ACDP program, the degradable plastics industry now has the tools it needs to ensure the credibility of claims for current and future generations of degradable plastic products.

The ASTM and ACDP biodegradable polymer programs have generated information on the performance of a benchmark set of materials that have been used by industry in comparing the performance of many newly developed materials. For example, the ACDP reported that the results obtained for the same material at each tier within the ASTM standard guide shows that for all materials compared, without exception, the degradation results obtained in a higher-level test equaled or exceeded those obtained in a lower-level test. This means that the laboratory scale ASTM D 5338, Test Method for Determining Aerobic Biodegradation of Plastic Materials Under Controlled Composting Conditions, was more conservative than the pilot-scale tests that, in turn, were more conservative than the full-scale tests. These observations have important ramifications with regard to environmental claims and the cost of generating data to support those claims. On the basis of the ASTM and ACDP program results, a material developer is able to generate a reliable and credible data package based upon relatively rapid laboratory- and pilot-scale tests that would be accepted by the governmental regulatory agencies and the general consumer.

Thus, from a state of confusion, misunderstandings, and legal actions by the attorneys' general task force and the FTC, the degradable plastics industry has begun to successfully introduce degradable plastics in the marketplace based on the technical strength and clarity of the developed ASTM standards and the ISR-ACDP program. Examples of this success can be found in U.S. Public Law 100-56, which requires degradable ring carriers for bottles and cans that cites ASTM D 5208, Standard Practice for Operating Fluorescent Ultraviolet (UV) and Condensation Apparatus for Exposure of Photodegradable Plastics, and D 3826, Practice for Determining Degradation End Point in Degradable Polyethylene and Polypropylene Using a Tensile Test, as the test methods to use to verify and confirm degradability. The state of Wisconsin's Department of Transportation in its procurement guidelines for erosion mat stakes cites ASTM D 5338 as its measure of biodegradability. That ASTM standard also forms the basis for the new standard D 6002, Guide for Assessing the Compostability of Environmentally Degradable Plastics. The presence and acceptability of the standards are attracting many companies to develop degradable plastics for a variety of applications.

Table 3. Sponsor Members of Advisory Committee on Degradable Polymers Program (ACDP)

Cargill

Dow Chemical

DuPont

Eastman Chemical

Ecochem

US Army Natick RD&E

KimberlyClark

Mobil Chemical

Novamont

Novon International

Procter & Gamble

Zeneca Bioproducts

National Com Growers Association

Association of the Nonwovens Fabrics Industry (INDA)

In the United States, multinational companies such as Cargill-Dow (a joint venture of Cargill and Dow Chemical), Eastman Chemical, DuPont, Monsanto, Union Carbide, and National Starch and Chemical are commercializing biodegradable plastics. In addition, there are a number of small- and medium-size companies that are also actively pursuing commercialization of degradable plastics. The 170-member strength of subcommittee D20.96 is indicative of this strong activity in the area of degradable plastics.

On the international level, the ASTM standards have led the way for the CEN, DIN, and ISO standards. Asian countries such as Japan, Taiwan, and Korea are using the ASTM standards as the basis for developing and using biodegradable plastics. Some of the major international companies involved in biodegradable plastics are Bayer and BASF (Germany), Novamont (Italy), Showa High Polymer, Mitsui Toatsu, and Shimadzu (Japan).

These companies and their new biodegradable thermoplastic technologies target a broad list of applications such as:

- Starch-based loose fill and rigid foam pack-

Standard Specification for Compostable Plastics A Milestone Achieved

A major milestone was met with the approval of the Specification for Compostable Plastics (D 6400). This standard establishes criteria (specifications) for plastics and products made from plastics to be labeled compostable. It establishes whether plastics and products made from plastics will compost satisfactorily, including biodegrading at a rate comparable to known compostable materials. This specification is comparable to what is being developed by the European Committee for Standardization (CEN) in Europe today, and in harmony with the Deutsches Institut für Normung (DIN) standard, moving the industry closer to global standards. The specification is based on and references three other D20.96 standard documents for the testing and identification of plastics that will biodegrade and compost satisfactorily. They are:

D 6002, Guide for Assessing the Compostability of Environmentally Degradable Plastics—Outlines recommended procedures and a general approach to establish the compostability of plastics. It provides a three-tiered criteria-based approach that includes rapid screening tests, laboratory and pilot scale composting assessment, and field/full scale assessment.

D 5338, Test Method for Determining Aerobic Biodegradation of Plastic Materials Under Controlled Composting Conditions—Determines the degree and rate of aerobic biodegradation of plastic materials on exposure to a controlled-composting environment under laboratory conditions.

D 6340, Test Method for Determining Aerobic Biodegradation of Radiolabeled Plastic Materials in an Aqueous or Compost Environment—Determines the rate and degree of biological oxidation of carbon in plastic materials when placed in a composting environment containing simulated municipal solid waste or an aqueous environment under laboratory conditions. It applies to plastics the biodegradation rate of which is slow and requires test periods of as long as 365 days.

These documents are based on the results of the work of Subcommittee D20.96 on Environmentally Degradable Plastics and several years of research conducted by ASTM's Institute for Standards Research at the request of D20.96.

aging;
- Packaging materials for single- or limited-use disposable packaging and film applications;
- Disposable nonwovens and hygiene products;
- Consumer goods—items such as cups, plates, cutlery, containers, egg cartons, combs, razor handles, toys, etc.;
- Coatings for paper and film; and
- Marine plastics—fishing lines, nets, pots etc., plastics used in ships (MARPOL treaty).

Film applications in single-use disposal packaging and select non-packaging disposal applications represent the best opportunity for biodegradable plastics. The film applications that are the most promising and having immediate potential are in:
- Lawn and leaf compost bags;
- Agricultural film; and
- Retail carry-out packaging bags (tee-shirt and other merchandise bags, garment bags, grocery bags, etc.).

One of the most promising applications for the use of biodegradable plastics is lawn and leaf waste compost bags. Steady growth in the yard waste-composting infrastructure in recent years has created a renewed demand for biodegradable compost bags. The EPA reports that 20 percent of the 32.8 million metric tons of yard trimmings generated in 1993 were delivered to central composting facilities. This amounts to approximately 6.6 million metric tons (14 billion lb) of yard trimmings collected primarily in polyethylene bags, but also in kraft paper compost bags or in bulk. Based on this amount of yard trimmings, the potential annual market for compost bags is 450 million 30-gallon (114 L) bags (assuming that one 30-gallon compost bag holds on average 30-33 pounds (13.5 to 15 kg) of yard waste). This translates to 56 million pounds (25 000 metric tons) of resin (estimating that one pound of resin yields eight 30-gallon bags of 1.5 mil thickness) (1 kg of resin yields 18 bags of 38 micrometre thickness). It is estimated that yard waste composting grew to 20 billion lb (9 million metric tons) in 1994, providing an 83 million lb (38,000 metric ton) market potential for compost bags. The market for compost bags will continue to grow as the composting infrastructure expands. Centralized yard waste composting facilities have grown from 651 in 1988 to 2,980 in 1992 and continues to grow. This dramatic increase in the number of composting facilities is complemented by increased throughput by existing facilities, resulting in further demand for compostable bags.

Twenty states now mandate composting of lawn and leaf waste, and many more will follow this trend. in addition, because of their biodegradability, state regulations increasingly require the use of paper bags instead of plastic. Biodegradable plastic bags are lighter, and have better strength and water resistance than paper. In the future, it is likely that the composting of other waste streams, such as food waste, will be required. This will also increase the size of the market for biodegradable plastics.

Conclusions

ASTM standards have helped define and grow a new degradable plastics industry—that was not accepted by the consumer and was looked upon warily by regulators—to a strong, thriving industry attracting large multinational companies commercializing biodegradable plastics worldwide. This paper showcases the impact of not only the ASTM standards, but ASTM itself and its ability to continuously evolve to respond to current needs with programs such as ISR, which was so vital for the degradable plastics standards.

Companies, researchers, and consumers will continue to turn to ASTM and its team to help define and grow the next generation of products, technologies, and services as the degradable plastics industry has. **SN**

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