

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/6437742>

# Compostability of Bioplastic Packaging Materials: An Overview

Article in *Macromolecular Bioscience* · March 2007

DOI: 10.1002/mabi.200600168 · Source: PubMed

CITATIONS

570

READS

5,600

6 authors, including:



**Gaurav Kale**  
FreshRealm

17 PUBLICATIONS 1,415 CITATIONS

[SEE PROFILE](#)



**Thitisilp Kijchavengkul**  
Mahidol University

33 PUBLICATIONS 2,076 CITATIONS

[SEE PROFILE](#)



**Rafael Auras**  
Michigan State University

309 PUBLICATIONS 19,200 CITATIONS

[SEE PROFILE](#)



**Maria Rubino**  
Michigan State University

88 PUBLICATIONS 6,431 CITATIONS

[SEE PROFILE](#)

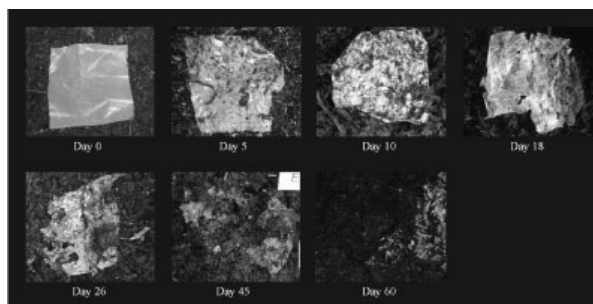
All content following this page was uploaded by Gaurav Kale on 05 August 2019.

The user has requested enhancement of the downloaded file.

# Compostability of Bioplastic Packaging Materials: An Overview

Gaurav Kale, Thitisilp Kijchavengkul, Rafael Auras,\* Maria Rubino, Susan E. Selke, Sher Paul Singh

Packaging waste accounted for 78.81 million tons or 31.6% of the total municipal solid waste (MSW) in 2003 in the USA, 56.3 million tons or 25% of the MSW in 2005 in Europe, and 3.3 million tons or 10% of the MSW in 2004 in Australia. Currently, in the USA the dominant method of packaging waste disposal is landfill, followed by recycling, incineration, and composting. Since landfill occupies valuable space and results in the generation of greenhouse gases and contaminants, recovery methods such as reuse, recycling and/or composting are encouraged as a way of reducing packaging waste disposal. Most of the common materials used in packaging (i.e., steel, aluminum, glass, paper, paperboard, plastics, and wood) can be efficiently recovered by recycling; however, if packaging materials are soiled with foods or other biological substances, physical recycling of these materials may be impractical. Therefore, composting some of these packaging materials is a promising way to reduce MSW. As biopolymers are developed and increasingly used in applications such as food, pharmaceutical, and consumer goods packaging, composting could become one of the prevailing methods for disposal of packaging waste provided that industry, governments, and consumers encourage and embrace this alternative. The main objective of this article is to provide an overview of the current situation of packaging compostability, to describe the main mechanisms that make a biopolymer compostable, to delineate the main methods to compost these biomaterials, and to explain the main standards for assessing compostability, and the current status of biopolymer labeling. Biopolymers such as polylactide and poly(hydroxybutyrate) are increasingly becoming available for use in food, medical, and consumer goods packaging applications. The main claims of these new biomaterials are that they are obtained from renewable resources and that they can be biodegraded in biological environments such as soil and compost. Although recycling could be energetically more favorable than composting for these materials, it may not be practical because of excessive sorting and cleaning requirements. Therefore, the main focus is to dispose them by composting. So far, there is no formal agreement between companies, governments and consumers as to how this packaging composting will take place; therefore, the main drivers for their use have been green marketing and pseudo-environmental consciousness related to high fuel prices. Packaging compostability could be an alternative for the disposal of biobased materials as long as



G. Kale, T. Kijchavengkul, R. Auras, M. Rubino, S. E. Selke,  
S. P. Singh  
School of Packaging, Michigan State University, East Lansing,  
MI-48823-1223, USA  
Fax: +1 517 353 8999; E-mail: aurasraf@msu.edu

society as a whole is willing to formally address the challenge to clearly understand the cradle-to-grave life of a compostable package, and to include these new compostable polymers in food, manure, or yard waste composting facilities.

## Introduction

Packaging waste is a major contributor to the generation of municipal solid waste (MSW). In the USA, containers and packaging waste accounted for 74.8 million tons (31.6% of the total MSW) in 2003,<sup>[1]</sup> 56.3 million tons (25% of the total MSW) generated in Europe<sup>[2]</sup> in 2005, and 3.3 million tons (10% of the total MSW) in Australia<sup>[3]</sup> in 2004. Currently in the USA, the most dominant method of packaging waste disposal is landfill, followed by recycling, incineration and composting. However, landfilling results in the generation of greenhouse gases and takes up and may contaminate land that could be used in the future. Hence, recovery methods like recycling or composting could be more desirable ways of packaging waste disposal. The common materials used in packaging are steel, aluminum, glass, paper, paperboard, plastics, and wood, all of which could be efficiently recovered through recycling. Paper and wood can also be recovered through composting. Biodegradable polymers also provide composting as a waste disposal option.

Composting is a natural process by which organic material is decomposed into a soil-like substance, called humus, a soil conditioner. Decomposition is mainly performed by microorganisms (mesophilic and thermophilic), including bacteria, fungi, and actinomycetes. These microorganisms use organic matter as their food source, generate CO<sub>2</sub>, and produce humus as an end product. This natural process requires availability of carbon, nitrogen, water, and oxygen. Microorganisms use carbon as a source of energy, and nitrogen for building cell structures. A 30:1 carbon-to-nitrogen ratio (C:N) is ideal for reproduction of thermophilic microorganisms, and makes the composting process faster.<sup>[4]</sup> A composting process goes through two main stages, an active composting stage and a curing period. In the first stage, the temperature rises and remains elevated, provided oxygen is available, which results in strong microbial activity. In the later stage, the temperature decreases but the materials continue to compost, at a slower rate. The compost process does not stop at a particular point; rather it continues slowly until the last remaining nutrients are consumed by the remaining microorganisms and almost all the carbon has been converted into carbon dioxide.<sup>[5]</sup> Aerobic composting takes place in the presence of oxygen; if oxygen is absent then the process changes to anaerobic digestion. Anaerobic digestion is also a naturally occurring process of decomposition and decay, by which organic matter breaks down into simple chemical components, producing biogas and

digestate (a relatively stable soil residue similar to compost). Biogas is a mixture of gases, mainly methane, which can be used for the production of heat and electricity, and carbon dioxide. The digestate can be used as a soil amendment, much like humus, for applications like farming or landscaping. The quality of compost produced in aerobic conditions is different from that produced in anaerobic digestion conditions, as different microorganisms are active.<sup>[5]</sup>

The majority of packaging materials used for food and medical packaging applications is disposed of by landfill, in part because of contaminants that are difficult to separate and may produce complications in recycling. In 2003, in the USA, 11.9 million tons of plastics packaging was generated, out of which only 1.06 million tons (8.9%) was recovered through recycling. Composting provides a viable option for recovering waste packages by returning them to nature.

According to the American Society for Testing and Materials (ASTM), a biodegradable plastic is a plastic that degrades because of the action of naturally occurring microorganisms such as bacteria, fungi, and algae. There is a difference between a biodegradable and a compostable plastic. A compostable plastic is 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 residues. Therefore, all compostable plastics are biodegradable, but the reverse is not true.

Biodegradation of plastics depends on both the environment in which they are placed and the chemical nature of the polymer. Biodegradation is an enzymatic reaction; hence it is very specific to the chemical structures and bonds of the polymer. There are different mechanisms of polymer biodegradation. One common mechanism is hydrolysis, in which random non-enzymatic chain scission of ester groups leads to reduction in molecular weight. The hydrolysis process is affected by the rate of diffusion of water through the polymer. As mentioned before, the biodegradation of plastics depends on both environmental factors (i.e., temperature, moisture, oxygen, pH) and the chemical structure of the polymer. Biodegradable polymers usually contain ester, amide, or carbonate hydrolyzable bonds in the polymer backbone. The presence of these hydrolyzable functional groups increases the susceptibility to biodegradation. Other factors that affect biodegradability are crystallinity, molecular weight, and, in the case of copolymers, the copolymer composition.<sup>[6]</sup>



**Gaurav N. Kale** is a graduate student in the School of Packaging, Michigan State University, USA. He holds a Bachelor of Engineering degree in Electrical Engineering from the University of Pune, India, where his studies focused on energy conservation and wind energy in India. At the School of Packaging, he is involved in research on sustainable packaging with a focus on bioplastic materials and their biodegradability.



**Thitisilp Kijchavengkul** is currently a Ph.D. research assistant at the School of Packaging, Michigan State University. He holds a Bachelor of Engineering degree in Industrial Engineering from the Chulalongkorn University in Bangkok, Thailand (awarded in 2000) and a Masters degree in Packaging from the Michigan State University (2005). Since graduating, he has worked at the School of Packaging as a research assistant in the agricultural application of biodegradable materials. He is working on the development of biodegradable polymers and their application in packaging, and is specializing in Environmental Science and Policy. He won second prize for the graduate student poster competition at the Global Plastics Environment Conference, 2006, Atlanta in the topic of the "Development of an Automatic Laboratory Scale Respirometric System to Measure Polymer Biodegradability", which has since been published as an article in the Polymer Testing Journal. He is a member of the Society of Plastic Engineers.



**Rafael Auras** is an assistant professor in the School of Packaging, MSU, East Lansing, MI, USA. He holds a BSChE from the National University of Misiones, Argentina, a M.Sc. in Materials Science and Technology from the National University of San Martin, Buenos Aires, Argentina, and a Ph.D. on Packaging from the School of Packaging, MSU. He teaches courses in materials science, polymers, shelf life, and instrumental analysis. His research interests include edible and biodegradable polymers, mass and heat transfer phenomena in polymers, food product/package compatibility and interaction, and sustainable packaging systems. Dr. Auras has authored and coauthored a variety of publications, including peer reviewed articles and book chapters. Dr. Auras has been a Fulbright, CONICET, and AECL fellow. He is an active member in the food science, polymer, and the packaging fields and has substantial international experience.



**Maria Rubino** is an Assistant Professor in the School of Packaging, MSU. She holds a M.S. in Packaging from Michigan State University and a Ph.D. in Food Science from the University of Manitoba. Her research interests include mass transfer in packaging materials and packaging systems, compatibility of packaging material with food and chemicals, packaging sustainability, active packaging, and method development for packaging analysis. She teaches courses on packaging permeability and shelf life and the application of instrumental analysis on packaging.



**Susan E. Selke** is a Professor in the School of Packaging at Michigan State University. She holds M.S. and Ph.D. degrees in chemical engineering from Michigan State. Courses that she teaches include plastics packaging, packaging materials, packaging and the environment, stability and recycling of packaging materials, and analytical solutions to packaging design. Her research interests include plastics recycling, biodegradable plastics, biobased plastics, composites of plastics with natural fibers, lifecycle assessment, nanotechnology and packaging, mass transfer characteristics of plastics, and other topics. She has authored or coauthored several books on packaging materials and on packaging and environmental issues, as well as over 150 articles and book chapters.



**Sher Paul Singh** is a Professor in the School of Packaging at Michigan State University. He holds an M.S. in Packaging and a Ph.D. degree in Agricultural Engineering. He researches and teaches in the areas of packaging, transportation and storage environment, machinery and automation. He has served as a consultant to various Fortune 500 companies and federal agencies such as the U.S. Army, Department of Justice, and United Nations, solving technical problems in packaging, material handling, and transportation. Dr. Singh was selected by NASA for the Advanced Life Support review of the Bio-Plex (Manned Mission to Mars) project. Dr. Singh has been retained as a consultant in over two hundred cases to assist various law firms, corporations, insurance companies, and the Department of Justice, providing expert opinion and testimony in civil and federal litigation in packaging, product liability, and patent infringement. Dr. Singh has published in a wide range of packaging and engineering journals on his various studies. He is also a contributing author in four books in the areas of packaging, material handling, and forensics.

Standards have been developed by ASTM and ISO (International Standards Organization) for the assessment of the biodegradability of polymers in different environments such as composting, anaerobic digestion, and wastewater treatment. According to ASTM standard D6400,<sup>[7]</sup> a product is compostable if it passes the tests of disintegration, biodegradation, and terrestrial and aquatic safety in

controlled laboratory scale composting. Similarly, there is a standard developed by ISO (EN 13432)<sup>[8]</sup> specifically for packaging, which assesses packaging compostability based on characterization, biodegradation, disintegration, and quality of compost or ecotoxicity. Characterization of packaging includes analysis of the composition of package materials, heavy metals, organic carbon content, total dry

solids, and volatile content. Detailed procedures and their harmony with other standards are discussed later.

A number of certification systems which provide compostable packaging labels have been established worldwide for certification of compostable plastics. Some of these labels are based on standards developed by ASTM, ISO, DIN (Deutsches Institut für Normung), and JIS (Japanese Industrial Standards). These certification systems include "DIN CERTCO" based on DIN EN 13432, "OK Compost" by AIB Vincotte (Belgium) based on EN 13432,<sup>[8]</sup> "Compostable" by the U. S. Composting Council based on ASTM D6400,<sup>[7]</sup> and the "GreenPla" certification by the Biodegradable Plastics Society (Japan) based on JIS K6953, to mention a few. JIS K6953 is reported by the Japanese Industrial Standards Committee to be identical to ISO 14855.<sup>[9]</sup>

Currently, biodegradable bags that are certified by the U. S. Composting Council as compostable are being used in San Francisco for transportation of compostable materials to the composting facility and composted along with other materials.<sup>[10]</sup> According to the American Forest & Paper Association (AF&PA) in America, about 6.5 million tons of postconsumer paper and paper products are produced annually that may be better suited for composting than recycling. This includes paper yard bags, waxed corrugated containers, milk cartons, paper plates, cups, napkins, and towels. In 1999, 300 000 to 325 000 tons of postconsumer paper was composted.<sup>[11]</sup> In the case of plastics, non-biodegradable plastics still dominate packaging applications and hence eliminate the option of composting.

Compostable polymers are being promoted as environmentally beneficial, especially if they can be derived from renewable resources and recovered through organic recycling. To evaluate the environmental performance of biobased products, a standard practice has been developed and presented in ASTM D7075<sup>[12]</sup> and ISO 14000 using life cycle assessment (LCA). LCA is a cradle-to-grave analysis tool developed for the assessment of the total environmental performance of a product (or process) and the system used for manufacturing, use, and disposal (or recovery) of that product. Currently, LCA studies of biobased polymers generally show reduced environmental impact and energy use when compared to petroleum-based polymers. For example, polylactide, PLA, derived from starch utilizes 0 GJ·ton<sup>-1</sup> of feedstock energy and 53 GJ·ton<sup>-1</sup> of processing energy, as compared to poly(ethylene terephthalate), PET, which utilizes 39 GJ·ton<sup>-1</sup> of feedstock energy and 38 GJ·ton<sup>-1</sup> of processing energy.<sup>[13]</sup> Furthermore, if PLA is disposed through composting and the compost is used in agriculture, significant emission and energy credits can accrue because of the value of the compost in sustainable agriculture practices, which can improve even further the sustainability of this biobased polymer.

The objective of this paper is to explore the current status of compostability of bioplastic packaging based on compostability mechanisms, the current status of composting, standards relevant to the compostability of packaging materials, and life cycle analysis of the performance of biodegradable packages based on composting as a disposal option.

## Compostable Packages

Packaging materials, as previously mentioned, can be divided into four groups: paper/paperboard, plastic, metal, and glass packages. Only paper/paperboard, and some plastic packages are biodegradable and, hence, compostable. ASTM defines a compostable plastic as a plastic that undergoes degradation by biological processes during composting at a rate consistent with other known compostable materials.<sup>[7]</sup> Therefore, only materials that biodegrade in composting environments and match the composting period of known compostable materials can be considered as 'compostable'. Not all biodegradable materials are compostable.<sup>[7]</sup>

## Compostable Materials

There are two main factors that make a material compostable: the material itself and the microorganisms in the compost. The material must be biodegradable, such as paper/paperboard and biodegradable polymers, which can be consumed by microorganisms as food sources. A compost pile is a great source of microbial activity, because it has a high moisture content and temperature, so it is a suitable environment for a variety of microbes, such as bacteria and fungi, to live and reproduce. This in turn provides a tremendous amount and variety of organisms able to attack and digest compostable materials. Bacteria can be either aerobic or anaerobic, while fungi are strictly aerobic. In both cases, the degradative reaction proceeds by production of enzymes that break down organic substrates to provide nutrients.<sup>[14]</sup> The enzymatic mechanisms can be divided into two categories: enzymatic oxidation (by aerobic microorganisms only), and enzymatic hydrolysis (by either aerobic or anaerobic microbes). The biodegradation mechanisms of the main packaging materials differ. Therefore, in this overview, the degradation mechanisms are described by material, and will mainly concentrate on the degradation of bioplastics.

## Biodegradable Polymers and Degradation Mechanisms

Since biodegradation is an enzymatic reaction, it is very specific to chemical bonds and structures of particular

functional groups. Microorganisms can attack only specific functional groups at specific sites, and the polymer chain also has to be conformationally flexible enough to fit into the active site of the enzyme. The meaning of conformational flexibility is defined later. There are various types of biodegradable polymers, with differing degradation mechanisms, so we will discuss them separately: 1) natural polymers, 2) carbon chain polymers, and 3) hetero chain polymers.<sup>[14]</sup>

#### Natural Polymers

As mentioned earlier, microorganisms can directly consume natural polymers like starch, cellulose, and polymers based on starch, since enzymatic reactions can reduce their molecular weight in extracellular environments, i.e., outside the microorganisms' cells. The polymer chains are enzymatically cleaved, and the portions that are small enough are transferred into the cells and consumed. The biodegradation rate of these polymers can be accelerated by hydrolysis which involves random chain scission, which results in rapid molecular weight reduction. The resulting smaller molecules are much more susceptible to enzymatic attack, making the polymer degrade much faster.

Another type of natural polymer is 'bacterial polyester', poly(hydroxyalkanoate)s, or PHAs. These natural polyesters are produced by bacteria as 'intercellular reserve materials' when they are fed carbon sources such as sugar or lipids but nutrients are restricted. The polymers are then extracted from the bacterial cells.<sup>[14]</sup> PHAs are aliphatic polyesters; the most common are poly( $\beta$ -hydroxybutyrate) or PHB, and poly(hydroxybutyrate-valerate) or PHBV, see Figure 1. The degradation mechanism starts with rapid enzymatic hydrolysis to cleave the ester bonds present in the polymer structure using extracellular depolymerases, such as those produced from *Pseudomonas lemoignei* and *Alcaligenes faecalis*.<sup>[15]</sup>

#### Carbon-Chain Polymers

Vinyl polymers, such as poly(ethylene), poly(propylene), and poly(vinyl chloride), with carbon-only backbones, are normally not susceptible to hydrolysis or to biodegradation. An exception is poly(vinyl alcohol) or PVOH, which is biodegradable because of its high hydrolyzability. The enzymatic oxidation of hydroxy groups (-OH) forms carbonyl groups (C=O) in the polymer backbone, and hydrolysis of two carbonyl groups (-CO-CH<sub>2</sub>-CO-) causes polymer chain cleavage, which leads to a decrease in molecular weight.<sup>[14,16]</sup> Microbes will then consume those low-molecular-weight portions.

#### Hetero-Chain Polymers

Hetero-chain polymers are polymers that have atoms other than carbon, such as oxygen and nitrogen, in their

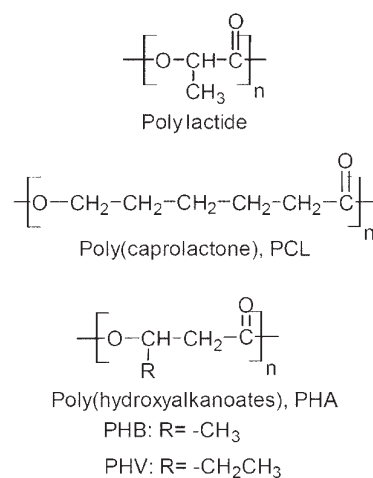


Figure 1. Structures of poly(lactide), poly(caprolactone), and poly(hydroxyalkanoate)s.

backbones. Those atoms make the polymers susceptible to hydrolysis (i.e., in which random non-enzymatic chain scission of the ester groups leads to reduction in molecular weight), and, therefore, can make them susceptible to biodegradation. Most synthetic hetero-chain polymers, such as polyesters, nylons, polycarbonates, etc., do not biodegrade to any significant extent.

Currently, the most common hetero-chain biodegradable polymers are PLA, poly(glycolic acid) (PGA), and poly( $\epsilon$ -caprolactone) (PCL). The bacterial polyesters such as PHAs also fit in this category. The higher the rate of hydrolysis, the more available sites there are for microbes to attack, and hence the faster is the biodegradation. Polymer hydrolysis is controlled in part by the rate of diffusion of water in the amorphous regions of the polymer.<sup>[6]</sup> Water diffusion through crystalline regions is negligible. Some plastics, such as PLA, will not biodegrade without prior hydrolysis.

The biodegradable polymers that have a promising future for packaging applications are mainly aliphatic polyesters, such as PLA, PCL, and PHA<sup>[14,15]</sup> (see Figure 1), and also include poly(tetramethylene adipate/terephthalate) (PTMAT), poly(butylene succinate) (PBS), poly(butylene succinate adipate) (PBSA), and some polyesteramides, since their properties are comparable to petroleum-based polymers commonly used in the packaging industry. For example, PHBV is hydrophobic and also provides an excellent gas barrier.<sup>[14,15]</sup> Temperature stability and processability of PLA are comparable to those of polystyrene; oil and grease resistance and flavor barrier properties are comparable to PET; and sealing temperature is lower than poly(ethylene) and poly(propylene).<sup>[17,18]</sup> Almost all of these polymers contain at least one of the following hydrolyzable bonds in the polymer backbone: ether, ester, amide, or carbonate.<sup>[6]</sup> While C-C linkages

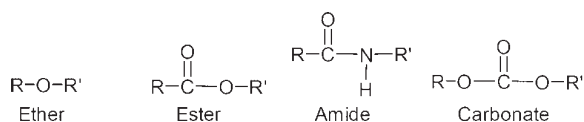


Figure 2. Hydrolyzable functional groups commonly found in biodegradable polymers.

increase stability, the presence of hydrolyzable functional groups in the polymer backbone dramatically increases the susceptibility to biodegradation<sup>[19]</sup> (see Figure 2), since it not only increases the vulnerable sites for hydrolysis but also the polymer flexibility,<sup>[20]</sup> so that the polymer chains can more easily arrange themselves to fit into the active sites of the enzymes.

The performance of hydrolyzable biodegradable polymers is primarily dependent on their erosion mechanisms, especially if they are intended for use in medical applications, such as drug delivery agents, or in agricultural applications, such as nutrient releasing agents in fertilizer.<sup>[6]</sup> There are two modes of erosion: surface erosion and bulk erosion. Enzymatic degradation caused by microbes occurs only at the polymer surface, while non-enzymatic hydrolysis can occur throughout the polymer's bulk because water can diffuse through the amorphous regions of the polymer. Both reactions usually happen at the same time, and compete with each other. If water-induced hydrolysis is faster than the enzymatic degradation, then the polymer tends to degrade throughout its cross section, in 'bulk erosion'.<sup>[6,17,21]</sup> On the other hand, if the enzymatic degradation is faster, then 'surface erosion' predominates.<sup>[6,17]</sup> These erosion mechanisms play a very important role in determining the applications of a biopolymer. For instance, if a polymer is used as a drug delivery agent and the active ingredient is located in the polymer surface, polymers that mostly undergo surface erosion will release the compound faster; on the other hand for a slow release drug, a polymer that undergoes bulk erosion will be more suitable so the active ingredient contained in the polymer matrix can be released over a longer period of time.<sup>[6]</sup>

### Factors Affecting the Rate of Biodegradation

Factors affecting biodegradation rates can be categorized as: 1) the exposure conditions, and 2) the polymer itself.<sup>[20]</sup>

#### Exposure Conditions

##### Water or Moisture

Water or moisture can affect the biodegradation of polymers in two ways. First, water is needed for microorganisms to grow and reproduce. Therefore, when moisture is plentiful, there should be more microbial activity, and

polymers should degrade faster. Second, since hydrolysis plays a fundamental role in biodegradation for some polymers, in moisture-rich environments hydrolysis reactions should increase, which produces more chain scission reactions and increases the available sites for microorganisms to attack. Kai-Lai et al.<sup>[22]</sup> found that degradation rates increased tremendously as the relative humidity of the exposure conditions increased. They determined that the molecular weight loss of PLA films exposed to 10, 50, and 100% relative humidity (RH) in an environmental chamber at 55 °C was 3 972, 61 947, and 121 836 Da per week, respectively. Therefore, it can be expected that polymers will biodegrade faster in moisture-rich environments than in dry conditions. However, we should keep in mind that in this particular case the main PLA degradation mechanism is hydrolysis, which enhances the impact of this factor.

##### Acidity

For hydrolyzable polymers, the rate of hydrolysis reactions can also be altered by pH, since reactions can be either acid or base catalyzed. For instance, it was found that the hydrolysis rate of PLA capsules was slowest at a pH of 5.0 and increased in more acidic and more alkaline solutions.<sup>[17,21]</sup> Degradation products, such as water-soluble lactic acid from PLA, can change the pH of the exposure environment. Changes in pH affect not only the rate of hydrolysis, but also the growth of microorganisms.

##### Temperature

Temperature is a significant factor in controlling polymer biodegradation since both hydrolysis reaction rates and microbial activity increase as temperature increases; however, if temperatures are too high, microbial activity decreases or even stops. Kai-Lai et al.<sup>[22,23]</sup> reported that the average degradation rate of PLA films at 25, 40, and 55 °C and 100% RH in an environmental chamber was 4 691, 40 634, and 91 892 Da per week, respectively. Therefore, moderately increasing the exposure temperatures enhances the degradation rate of PLA, at least in part as a result of increasing the rate of hydrolysis. A study performed by Cargill Dow LLC also showed that the hydrolysis rate of PLA increased dramatically above the glass transition temperature ( $T_g$ ).<sup>[21]</sup> Furthermore, different microorganisms can grow and reproduce at their best at different temperatures. In general, the rate of biodegradation increases with temperature, as long as it is not high enough to kill the microorganisms.

##### Aerobic or Anaerobic Conditions

In aerobic biodegradation, the microorganisms use oxygen and consume carbon from the polymer as a food source; as a result carbon dioxide and water are produced and

released. This corresponds to enzymatic biological oxidation. This reaction predominates if a high oxygen concentration (not less than 6%, as described in ASTM D5338<sup>[24]</sup>) is available. If the oxygen supply is depleted, aerobic microorganisms will change their metabolism rate, which causes a reduction of the biodegradation rate. On the other hand, in anaerobic biodegradation, anaerobic microorganisms consume carbon from the polymer and release methane and carbon dioxide. Each kind of microorganism may consume carbon from polymers at a different pace; therefore, biodegradation of polymers in aerobic conditions may be totally different than that in anaerobic conditions. For example, as reported by Gartiser et al.,<sup>[25]</sup> PCL did not biodegrade, and PLA was found to biodegrade at a minor level (less than 10%) under anaerobic conditions based on ASTM D5511<sup>[26]</sup> and ISO 14853<sup>[27]</sup> test methods.

### Enzyme Specificity

Different enzymes may have differently shaped active sites and, therefore, are more able to biodegrade certain polymers. For example, the fungi *Aspergillus niger* and *Aspergillus flavus* produce enzymes that more readily degrade aliphatic polyesters derived from diacid monomers with 6–12 carbon atoms than those derived from other monomers.<sup>[14]</sup> It was found that extracellular PHB depolymerases, enzymes that depolymerize PHB, degrade PHB by different mechanisms depending on the specific bacteria producing those enzymes.<sup>[15]</sup> Therefore, different microorganisms consume specific polymers at different rates.

### Polymer Factors

#### Polymer Structure and Chain Flexibility

The 'flexibility' (conformational flexibility) of a polymer chain indicates how much energy it takes to rotate molecules around bonds and how easy it is to move atoms closer to or further away from others. If a polymer chain is more conformationally flexible, more sites will be accessible to water for hydrolysis, and the polymer will more easily fit into the active sites of enzymes; both of these will increase the biodegradation rate. Two factors that affect the polymer's conformational flexibility are bulky side groups that limit chain movement and certain types of linkages in the polymer backbone.

Side groups increase the energy required for chain rotation. For example, poly(glycolic acid), Figure 3 (left), degrades faster than polylactide, Figure 3 (right), in part because the polylactide chain is less flexible because of the methyl ( $-\text{CH}_3$ ) side group that inhibits chain movement.<sup>[20]</sup> The methyl side group reduces the water accessibility of the polymer chain as well as the biodegradation rate.



Figure 3. Left: poly(glycolic acid), right: polylactide.

Double bonds in the backbone increase flexibility by easing rotation around adjacent single bonds, as illustrated by the fact that the rotational barrier (energy required for rotation around the bond) of  $\text{CH}_3-\text{CH}_3$  is 3.0 kcal·mol<sup>-1</sup> while that of  $\text{CH}_2=\text{CH}-\text{CH}_3$  is only 2.1 kcal·mol<sup>-1</sup>. The presence in the backbone of oxygen or nitrogen also increases flexibility by lowering the rotation energy barrier;  $\text{CH}_3-\text{OCH}_3$  has a rotational barrier of 2.7 kcal·mol<sup>-1</sup>. A ring structure, on the other hand, decreases flexibility because it hinders chain rotation.<sup>[20]</sup> For example, the aromatic ring structure that provides rigidity for PET hinders water and enzyme access, making PET more environmentally stable than aliphatic polyesters.

### Crystallinity

As mentioned earlier, hydrolytic reactions are controlled in part by the rate of water diffusion into the polymer bulk in the amorphous regions, since water cannot diffuse through crystalline regions and amorphous regions are more flexible. Therefore, amorphous regions are more susceptible to both hydrolysis and biodegradation than crystalline regions.<sup>[6]</sup> For polymers like PHB, biodegradation occurs mainly by surface erosion as a result of enzymatic hydrolysis, and the main factors that control the rate of biodegradation were found to be the degree of crystallinity<sup>[15]</sup> and accessibility of the polymer chain to microorganisms. PLA with different degrees of crystallinity, as a result of different contents of L-lactide and D-lactide, has different degradation rates, because of the effect on the rate of hydrolysis.<sup>[17,28]</sup> PLA polymers with higher contents of D-lactide degrade much faster since D-lactide induces twists in the otherwise very regular poly(L-lactide) molecular architecture, which reduces crystallinity.

### Molecular Weight

Generally, plastics are immune to microbial attack if their molecular weights are high (e.g., for PLA,  $\bar{M}_w \geq 20\,000$  Da) because the molecules are too large to allow their entrance into the microorganisms' cells. Microorganisms can degrade only low-molecular-weight portions, which are taken into the cells and then converted into metabolites.<sup>[14]</sup> For natural polymers, such as starch and cellulose, microorganisms can attack the molecules directly since they can produce enzymes to cleave, or depolymerize, the natural polymer backbones, and consequently molecular weight reduction can happen outside the microbial cells.<sup>[14]</sup> For other biodegradable polymers, before being utilized by microorganisms, the molecular weights have to

be reduced to a point at which the molecules can enter the microbial cells by other means of degradation, such as hydrolysis or photodegradation. The upper limit of molecular weight that microbes can metabolize differs by polymer; for example, a critical molecular weight ( $\overline{M}_w$ ) for PLA is 10 000–20 000 Da,<sup>[17,21]</sup> and for PHB is approximately 13 000 Da.<sup>[14]</sup>

The molecular weight of a polymer affects the biodegradation rate in two different ways. As the molecular weight increases, the polymer's  $T_g$  also increases, which makes the polymer glassier and less flexible. Furthermore, a higher molecular weight polymer also has a longer chain length, which means that there are more bonds that must be cleaved in order to release the water-soluble oligomers or monomers that are small enough to be consumed by microorganisms.<sup>[6]</sup> Consequently, a polymer with a higher molecular weight biodegrades more slowly than the same polymer with a lower molecular weight.

#### Copolymer Composition

Introducing comonomers into a polymer structure will increase the irregularity of the polymer chains, which will generally reduce the polymer's crystallinity and thus may increase biodegradability. However, the effect also depends on the type of comonomer.<sup>[6]</sup> If the comonomer contains hydrolyzable groups, the biodegradability should be increased. On the other hand, if the comonomer contains aromatic structures, or other groups that provide rigidity to the polymer chain, and no hydrolyzable groups, the copolymer will generally have lower biodegradability or may not even biodegrade at all. Chiellini and Corti<sup>[29]</sup> reported that graft copolymerization of lignin with PCL was found to increase the biodegradability from 10% mineralization with pure lignin to 60% mineralization during a 100 d incubation period in mature compost at 55 °C.

#### Size and Shape

The size and shape of the exposed polymer also play an important role in biodegradation. Polymers with higher surface areas will degrade faster than those with lower ones, other factors being equal, since a larger fraction of the polymer is in contact with moisture and microorganisms for hydrolysis and enzymatic degradation. Both ASTM<sup>[7]</sup> and ISO<sup>[9]</sup> standards for biodegradability require control of size and shape during biodegradation testing.

## Composting

Composting is a biological process in which microorganisms convert organic materials such as manure, sludge, leaves, paper, and food waste into a soil-like substance called compost. Composting is an aerobic process (in the

presence of oxygen) as discussed earlier. Compost can be produced by commercial techniques involving turning mechanisms, sorting and shredding on a large scale; and also in small-scale backyard composting. Commercial composting is typically a much faster process than backyard composting, as it is managed more intensively and optimal conditions are maintained.

## Waste Materials

### Yard Waste

Yard waste can be defined as the vegetative waste that results from the care and maintenance of landscaped areas, lawns, and gardens. It may include leaves, grass clippings, garden wastes, tree trunks, and prunings from trees or shrubs. The C:N ratio of yard waste ranges from 9 to 80 (grass clippings 9–25, leaves 40–80, shrub trimmings about 53, tree trimmings about 16).<sup>[5]</sup> Sometimes, yard wastes are composted in passive piles (a method of composting in which there is little management and manipulation of the materials after they are mixed and piled). Yard waste is mostly generated from municipalities and landscapers.

In the USA, yard waste is commonly collected at the curbside or by public drop-off sites. Public drop-off sites are specified locations where residents and businesses can take their yard trimmings. In curbside collection, the municipality or concerned agency picks up yard trimmings that residents have placed outside of their homes.<sup>[30]</sup> Yard waste can be composted in either commercial composting facilities or by backyard composting. The Environmental Protection Agency (EPA) of the United States estimates that 3 800 yard waste composting facilities were in operation in 2000 in the USA.<sup>[31]</sup>

In Canada, leaf and yard trimmings are the most common materials composted, with 182 facilities in operation. Collection methods range from drop-off by private haulers and residents (135 facilities) to curbside residential programs (77 facilities, with the vast majority being either source-separated or wet/dry programs).<sup>[32]</sup>

In 2003 in Europe, 1 800 composting plants were in operation, 40% of which only included yard waste.<sup>[33]</sup> Victoria, Australia has contracts with composting companies to recycle green organic materials from yards and gardens with a capacity of over 100 000 metric tons per year. New South Wales diverts over 300 000 metric tons per year of organic materials with an estimate of 800 000 metric tons still to be diverted.<sup>[34]</sup>

New Zealand has undertaken a zero waste initiative with the goal of minimizing and eventually eliminating waste. There are growing numbers of composting facilities in New Zealand, and in 1999 approximately 23 000 cubic

meters of material was composted. In Christchurch, New Zealand, 70% of households recycle each week and about 60% compost at home or take green waste to the council's composting plant.<sup>[34]</sup>

According to the Japan Organics Recycling Association (JORA) the annual production of wood residuals such as bark, sawdust, and wood chips was about 5.34 million tons in 2001; about 95% of these residuals were utilized effectively. Yard waste as a result of pruning trees or trimming grass represented 6% (2.47 million tons) of total municipal solid waste in 2001.<sup>[35]</sup>

#### Food Waste

Food wastes mostly consist of uneaten food and food preparation wastes from residences, commercial establishments like restaurants, institutional sources such as school cafeterias, and industrial sources like factory lunchrooms. The C : N ratio of food wastes ranges from 14 to 80 (garbage food waste 14–16, and refuse 34–80).<sup>[5]</sup> The main source of food waste is usually garbage and refuse (mixed food and packaging) that results from mixed MSW. MSW is extremely heterogeneous in size, moisture, and nutrient content and will contain varying degrees of non-compostable and possibly hazardous wastes. Hence, sorting of MSW, using mechanical or manual techniques, plays an important role when it comes to composting of food waste. While some composting of mixed MSW is carried out, increasingly the composting of food waste is dependent on source separation, i.e., the waste generator separating food (perhaps along with other compostable wastes) from non-compostables. The food wastes may be pre-consumer, such as food processing or preparation wastes from institutional or industrial sources, or post-consumer, wastes from homes or from restaurant or institutional meals.<sup>[36]</sup>

Food waste has a high moisture content and little physical structure; hence normally it is mixed with a bulking agent such as yard waste for composting. In addition, food waste is very susceptible to odor production (ammonia) and tends to generate large quantities of leachate. Hence, normally a well aerated pile is recommended for composting food scraps.<sup>[36]</sup>

In 2005, in the USA there were 16 mixed MSW composting facilities in operation and 11 more that composted residential source separated food wastes.<sup>[37,38]</sup> In Canada, there are 54 facilities composting food residues from the residential sector.<sup>[32]</sup> Around 39% of the total 200 million tons MSW generated in Europe in 2000 was food scraps or food waste.<sup>[33]</sup> In Australia, food residuals comprise up to 41% of the domestic waste stream and 17% of the commercial/industrial stream. A food residuals processing facility was set up in the Melbourne metropolitan area that composts food scraps. EcoRecycle Victoria provided almost \$1.2 million to support infrastructure development for green organics and food residuals

Table 1. Food and yard waste generated during 2003 in the USA.

Waste <sup>a)</sup>	Generated	Composted
	10 <sup>6</sup> tons	10 <sup>6</sup> tons
Food	25.1	0.7
Yard	26	14.6
Total	51.1	15.3

<sup>a)</sup>Total amount of MSW in 2003 was 214.7 millions tons.

collection and processing.<sup>[34]</sup> JORA estimated an annual production of food residuals of 18 million tons in June 2001, out of which only 0.1 percent was composted; the majority was either landfilled or incinerated.<sup>[35]</sup> Table 1 shows the total amount of yard and food waste generated and composted in the USA during 2003.

#### Manure Waste

Manure is the faecal and urinary excretion of livestock and poultry. Manure waste may contain bedding, spilled feed, water, and soil as well as livestock excreta. It can be classified as liquid, semi-solid, slurry, or solid. Manure waste used in composting normally involves broiler litter, cattle manure, horse manure, laying hens, sheep, swine, and/or turkey litter or a combination of these. The C:N ratio ranges from 3 to 56. Most of the animal manures are rich in nitrogen content and hence are normally mixed with materials with higher carbon content to achieve an optimized C:N ratio for composting. Commercial composting is a more suitable way for handling manure waste than home/backyard composting.<sup>[5]</sup> In Canada, 39 facilities compost manure or animal waste. In 1998, finished compost production was around 845 400 tonnes, which included composting of manure waste, food waste, and yard waste.<sup>[32]</sup> In Japan, annual production of animal waste is around 94 million tonnes: 65 million tonnes of faeces and 29 million tonnes of urine. According to JORA, in 2001 94% of total animal excretion was recycled to farmland and grassland after drying or composting.<sup>[35]</sup>

#### Packaging Waste

Packaging waste is generated by the disposal of packaging materials such as paper and paperboard, plastics, steel, aluminum, glass, and wood. Steel, aluminum, and glass cannot be composted and must be separated prior to composting. A substantial amount of the paper and plastics in MSW come from packaging of food and consumer goods and is normally recycled, landfilled, or incinerated. In the USA, in 2003, 56.4% of paper and paperboard packaging was recycled while only 9% of plastics packaging was recycled.

Upon introduction and certification of compostable plastics, composting plants have started accepting compostable liner bags. For example in San Francisco, the composting facility accepts 'compostable liner bags' that contain food scraps. The compostable liner bags (commercially available and produced from corn starch) make it easier for residents to separate food scraps for compost collection.<sup>[39]</sup> In Massachusetts, the Massachusetts Department of Environmental Protection (MADEP) is encouraging composting of items such as spoiled fruits and vegetables, floral and deli wastes, and waxed cardboard from supermarkets through the Massachusetts Supermarket Organics Recycling Network. The main goal of this program is to divert to compost facilities the commercial food waste generated by supermarkets. MADEP identified supermarkets as a major generator of waste organics. They estimated that there are 400 supermarkets in the state generating around 90 600 tons of organics per year. Compostable liner bags that biodegrade quickly and safely are being used in this program to transport the materials from collection containers to the commercial composting facility.<sup>[40,41]</sup> Some commercial compostable bag brands are Bio-Bag (Canada), and EcoFilm and EcoWorks by Cortec Corporation (MN, USA).

Currently, researchers are demonstrating that compostable packages can be composted in facilities that handle yard waste and manure as well as in those that handle food wastes. Therefore, more options to compost biopolymers could be available if compostable biopolymers used in packaging applications were accepted by these compost facilities. Figure 4 and 5 show the degradation of PLA bottles and Ecoflex films under compost conditions (58 °C, 60% RH) after 30 and 60 d, respectively.<sup>[42–45]</sup>

As market incentives are created for green and environmentally friendly polymers, there is also interest in developing new compostable materials from petroleum resources.<sup>[46]</sup> As previously defined, a compostable material must completely biodegrade under standard compost conditions. Currently, some manufacturers are claiming compostability for polyolefin plastics containing additive technologies that are reported to work in a two-step process that accelerates oxidation and then biodegrades. The manufacturers claim the prodegradant additives control these processes in a highly predictable and manageable manner in all conditions with a

source of oxygen and naturally occurring microorganism (air, soil, landfill, compost, litter). The process is commonly referred to as 'oxo-biodegradation'. The main market for these polymers is biodegradable mulch film, but these need to be collected after the harvesting season if composting is the intended option for their disposal. According to manufacturers, these polymers are engineered to degrade and totally fragment in 90 to 120 d. After that 60% will mineralize/biodegrade in a further 12 to 24 months when disposed of in a commercial compost facility and in subsequent soil application.<sup>[46]</sup> Figure 6 shows a commercially available LDPE film with the oxo-biodegradation additive exposed to composting conditions for 60 d at  $48 \pm 5$  °C and  $52 \pm 16$  % RH. After 60 d in the compost pile, no visual fragmentation is observed. Therefore, further study of these polymers is necessary to determine whether the compostability claims can be substantiated.

### Composting Techniques

#### Commercial Composting

Commercial or municipal composting is a large scale operation, which generally employs turning and active aeration, except for static pile and some in-vessel com-

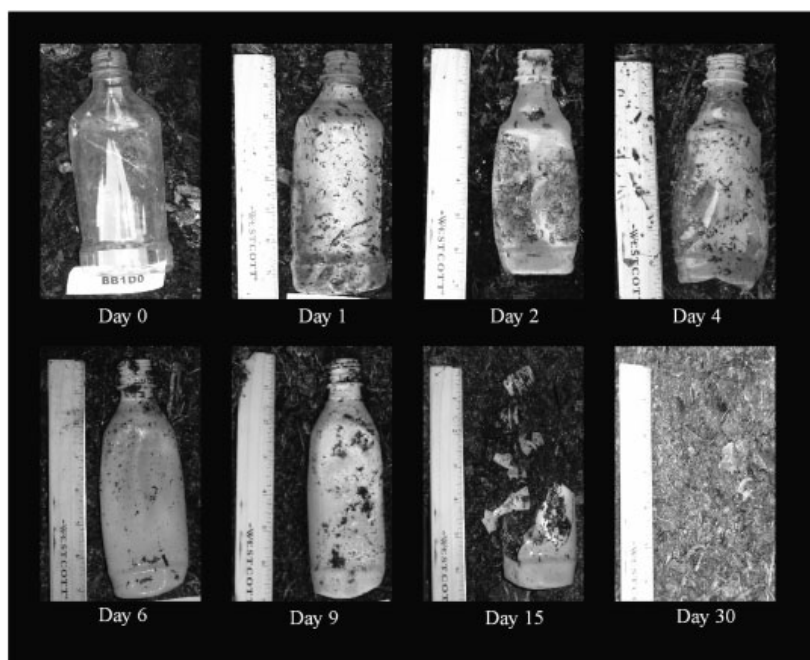
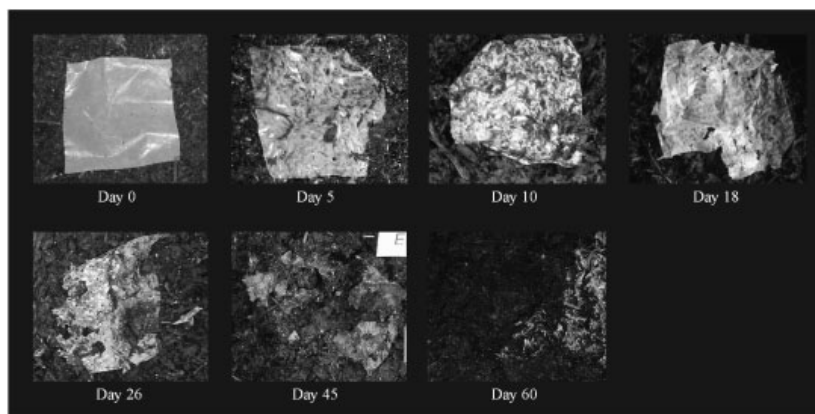


Figure 4. Pictorial view of PLA bottles exposed at 30 d of compost conditions ( $58 \pm 5$  °C,  $60 \pm 5$  % RH).<sup>[42,43]</sup>

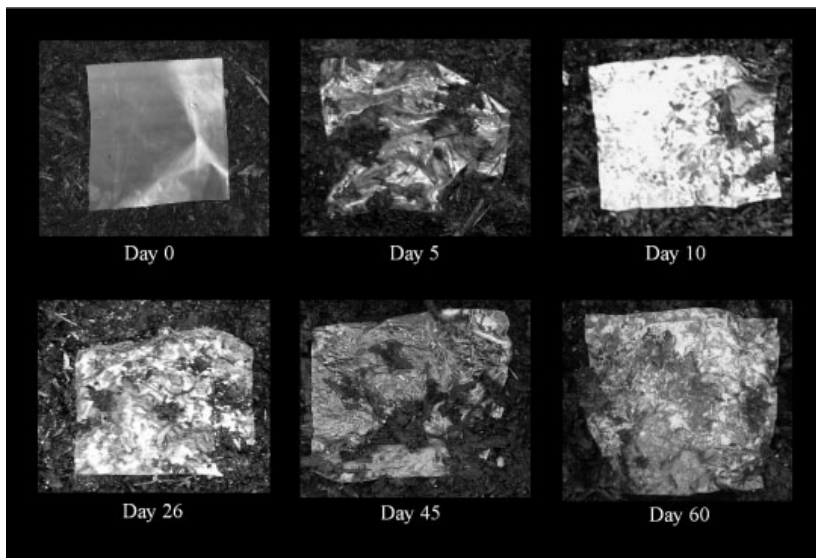


**Figure 5.** Pictorial view of Ecoflex films exposed for 60 d to compost conditions. ( $48 \pm 5^\circ\text{C}$ ,  $52 \pm 16\%$  RH).

posting systems. Since waste materials have different characteristics, operational parameters such as moving, mixing, and manipulation differ.

Composting begins with the collection of suitable organic materials, followed by mixing to achieve the desired C : N ratio, moisture content, and pore space. Usually one material is primary and then one or more amendments are added.<sup>[5]</sup> Raw material sorting is essential, especially if it is a mixed waste stream. Shredding or grinding is optionally employed if the raw materials include newspaper, corrugated cardboard, brush, tree stumps, or other large yard wastes. Grinding or shredding may use shear shredders (rotary or belt), hammer mills, or tub grinders.<sup>[5]</sup> In some of

windrow formation. Mixing can be simply done by repeatedly bucketing the ingredients together. Windrows and passive piles can be mixed and formed in a single step by depositing the raw materials on the composting site in layers, to form a crude pile. The loaders then mix the materials together and work them into the desired shape until the materials are well mixed. Other equipment used in mixing include batch mixers in which amendments are placed in the mixer and then the manure added on top. The mixture can be discharged through the side delivery elevator directly into the windrow, or onto an aerated pile as the mixer is pulled forward parallel to the air distribution pipe.



**Figure 6.** Pictorial view of LDPE with oxo-additive exposed for 60 d to compost conditions ( $48 \pm 5^\circ\text{C}$ ,  $52 \pm 16\%$  RH).

the in-vessel methods, the mixing step is built into the system. The material needs to be loaded into the silo, hopper, or vessel using conventional materials handling equipment such as conveyors, augers, or bucket loaders. Subsequent turning mixes the materials more thoroughly.

Frequent turning improves consistency and diminishes the importance of the initial mixing in windrow systems, relative to a static-pile system, where organic waste is formed into rows of long piles and aerated by turning the pile periodically. Bucket loaders play a very versatile role in composting operations by allowing mixing and pile/

After the active composting phase, compost requires a curing period of at least one month to finish the process and allow the compost to develop the desired characteristics for its intended use.

After curing, screening of compost separates materials of different sizes and/or shapes. Screening is nearly always performed after curing either to improve compost quality or to recover bulking agents. Different types of screens are available, including trommel screens, shaker screens, vibrating screens, flexing belt screens, disc screens, auger and trough screens, and rotary (spinning disc) screens.<sup>[5]</sup>

Drying follows after screening to lower the moisture content of the compost. It typically involves extra aeration or an extended composting period.

Figure 7 shows a flow chart of a complete commercial composting process.

Advances in Composting Techniques

Currently, source separated composting, in which the waste is separated by the consumers at the residential level, has gained a lot of attention in the USA, Canada, and Europe. In the USA, 11 residential source separated composting projects were active in the states of California, Michigan, Minnesota, and Washington in 2003.<sup>[38]</sup> The residential sorting and collection methods differ based on the composting facility. For example, in San Francisco, CA, a residential three source separation cart collection is employed which consists of organics, single stream recyclables, and trash.<sup>[38]</sup> Similarly in Canada, source separating MSW into wet and dry streams is a popular way to achieve waste diversion objectives, as it offers great flexibility in classification of waste streams, collection methods, collection frequency, and waste processing. About 98% of the consumers in Guelph, Canada, participate in the wet/dry two-stream program.<sup>[47]</sup> In Europe, the composting of mixed MSW is becoming rare because of growing recognition of the benefits of source-separated MSW composting. In 1998, around 85% of home composted or separately collected MSW was being recovered in Austria, Belgium, Denmark, Germany, and the Netherlands.<sup>[48]</sup> Those five nations have finalized their organic

waste policies based on source-separated MSW diversion and have achieved better recovery rates.<sup>[48]</sup>

In the case of mixed MSW, sorting is necessary. Goldstein<sup>[38]</sup> explained a typical composting process for a mixed MSW stream. Initially MSW is sorted to remove the oversized items and then passed by conveyor through a manual sorting step to remove inappropriate materials for composting. A bag breaker machine is used to remove wastes from the bags. This automated system consists of different diameter drums, which rotate at different speeds. They are equipped with hooks that grab the bags and elongate them as the drums spin, to spill out the contents from the bags. Next the waste is screened through a debris (disk) roll screen. The waste material obtained through the screen goes to an auger mixer, and the remaining material on the screen is moved to an optional sorting station where more recyclables can be removed. The mixer auger is equipped with knives, which help in reducing the particle size without shredding or grinding. Later, water is added to the mixture in the vessels to improve the moisture content. The vessels' aeration system is designed to minimize evaporation and maintain temperature levels. The vessels are later unloaded to form aerated static piles. After the compost is ready, it is screened to remove any foreign materials contained in the final product.

Savage et al.<sup>[52]</sup> provide an overview of screening and an introduction to air separation based on material density.

Air separation uses an air current to classify the waste materials; a typical air classification system begins with introduction of MSW materials through a chute into an upward flowing stream of air. The lighter materials are carried out with the air and the heavier materials fall onto a conveyor or into a bin. The lighter particles next enter into an air cyclone where they settle out. Air separation is a function of density, shape, and size of the particles and can be efficiently used in separation of plastic particles and film from the compost.<sup>[52]</sup>

Turning equipment is used for the mechanical agitation of piles to manage the temperature and oxygen levels. The windrow turners commonly used in commer-

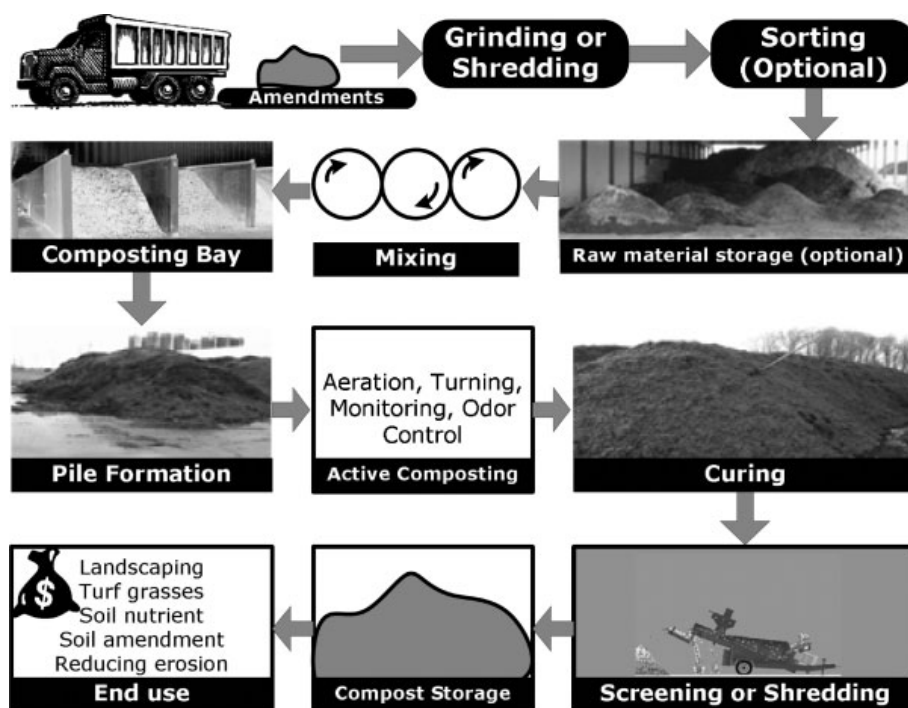


Figure 7. Commercial composting system and operations.

cial composting can be categorized by turning mechanisms, orientation to the windrow, power source, and mode of travel.<sup>[49,50]</sup> Some categories of turners based on their mechanical agitation are straddle type, auger equipped turner, elevating face, and trapezoid turners.<sup>[50]</sup> Some improvements in recently produced turners (as reviewed by Diaz et al.<sup>[50]</sup>) include better efficiency, increased durability, less maintenance, ability to accommodate large or different sizes of windrows, and increased ease of travel and transportation. Turner manufacturers are stressing the improvement of turning equipment for larger windrow sizes, which will help in the larger scale production of compost. More details regarding turning equipment and the turning process can be found elsewhere.<sup>[50]</sup>

The last step after the compost is produced is screening to remove foreign matter (FM) (undesirable materials such as plastic, metal, or glass). A recent study by Page et al.<sup>[51]</sup> compared three different screening methods for finished compost. One pass through a ball screen (resulting in 0.26% FM) and two passes through a trammel screen (0.53% FM) gave the best results.

#### Home Composting (Back Yard)

Home composting is handled on a small scale using small piles or composting bins. Turning is usually done manually unless the bins are equipped with rotating drums. Home composting usually involves lower temperatures than commercial composting, with much of the decomposition taking place at mesophilic temperatures (10 to 46 °C). Yard waste and food waste normally go into home composting systems,<sup>[5]</sup> but improper management of food scraps can cause odors and also might attract unwanted insects or animals.<sup>[31]</sup> In back yard composting, the conversion of organic matter into compost may take up to two years, but manual turning can decrease this time to 3 to 6 months.<sup>[31]</sup> Commercial backyard composting bins are typically either open or closed cylinders, revolving drums, or orbs that can be rolled along the ground to turn the pile. Recently there have been many developments in commercial indoor and outdoor composting bins, many of which are specifically designed to compost food scraps. An indoor kitchen composter developed in Japan anaerobically ferments food scraps using the patented Bokashi method<sup>[53]</sup> of beneficial microbial inoculation, which speeds up the microbial process. Some other systems have bins that contain three compartments which allows one to increase or decrease the volume and to classify fresh and mature compost or humus within the same bin. Also, as ventilation is important to maintain the aerobic process, some systems continuously circulate air throughout the bin. Some bins are also equipped with stirrers and screens, which turn and screen the compost.<sup>[53]</sup> In Seattle, Washington, households doing back yard composting of yard waste

had an annual household recovery rate of 254 kg and those who composted food waste recovered 131 kg.<sup>[53]</sup> In Canada, approximately 27% of homeowners in Edmonton are composting in their back yards, which diverts 10 224 tonnes of organic waste from landfill each year.<sup>[32]</sup>

#### Plastics in Compost

Synthetic plastic waste or particles in compost is a major contamination problem; hence plastic separation in compost is an important factor for both the compost feedstock and the compost end product. As mentioned above, different screening and separation mechanisms can be used to separate plastics from compost.

A case study on plastic-wrapped industrial food residuals was done in California, USA in 2005.<sup>[38]</sup> The composting facility received industrial food waste contained in plastic packaging, which was then ground with the green feedstock, composted, and foreign matter was subsequently screened out through a trammel screen. Plastics present in the compost floated through the trammel and were ejected over a belt equipped with an air knife. The plastic particles were sucked up through the air knife, leaving behind the bulking agents, which could be used again in the composting process.

Rynk<sup>[54]</sup> reported case studies about the contamination of compost as a result of plastics and other foreign particles. In one study, samples of MSW compost were inspected after repeated sieving, drying, and weighing. It was found that plastics (average 1.9% of compost dry weight) remained in the compost even after repeated sieving with sieve sizes of 1 to 4 mm. For larger compost size ranges (4 mm to <25 mm) the plastics contamination percentage ranged from 3.5 to 6.6% of the compost dry weight.<sup>[54]</sup> Another study found similar results for plastics contamination in sieved (1.875 mm) and non-sieved compost.<sup>[54]</sup>

De Baere<sup>[54]</sup> evaluated the replacement of biodegradable with synthetic polymers and their composting in commercial composting facilities, including cost analysis. The first case study was for a 50 000 ton · a<sup>-1</sup> Belgium-based source separated composting facility which had 80% of its organic waste delivered in plastic bags. The system included prescreening to remove the plastic material to avoid plastics contamination in the composting process and end product. According to De Baere,<sup>[54]</sup> the use of 500 tons of compostable biopolymer per year rather than non-compostable plastics would eliminate 2 000 tons · a<sup>-1</sup> of left overs from pre-screening since biodegradable plastic does not need this step.

#### Uses of Compost

Compost is a very valuable soil amendment that improves plant growth. Compost-enriched soil can also reduce

erosion, alleviate soil compaction, and help control disease and pest infestation in plants. In addition to common agricultural and horticultural applications, compost is used in some building and construction projects. On steep embankments along roads and highways, compost can be more effective than traditional hydromulch at reducing erosion and establishing turf because compost forms a thicker, more permanent growth as a result of its ability to improve the infrastructure of the soil. Because of the ability of compost to retain moisture, it also helps protect soil from wind erosion and during droughts. Compost is also used to remediate turf grasses that are extensively used for recreational activities such as golf, football, soccer, etc. Often the wear and tear on such turf results in disease, pests, and soil compaction. Use of compost increases resistance to growth of turf diseases, such as snow mold, brown patch, and dollar spot. Compost is an effective landscape mulch; when placed over the roots of plants, compost mulch conserves water and stabilizes soil temperatures. It also helps keep plants healthy by controlling weeds, providing a slow release of nutrients, and preventing soil loss through erosion.<sup>[55,56]</sup>

#### Environmental Impacts of the Composting Process – Leachate

Leachate is the liquid that results when water comes in contact with a solid and extracts material, either dissolved or suspended, from it.<sup>[5]</sup> Leachate differs from other water that may accumulate on a compost site through precipitation or flooding since leachate may contain a combination of nutrients, soluble chemicals, and organic matter. Hence, good drainage at composting sites is necessary.

Leachate management can be achieved in different ways, which include providing a slope for easy run off, maintaining sufficient distance between compost and ground water facilities, maintaining the moisture content of compost below the maximum recommended level, and encouraging effective drainage by orienting windrows with the slope of the compost pad rather than across it.

In Canada, leachate is either disposed through local waste water systems, released to engineered wetlands to purify it, or released through natural purification systems.<sup>[57]</sup> In Europe, leachate is used for watering the composting mass or is discharged.<sup>[58]</sup> In Australia, containment of leachate within the composting area is required. It can be used for irrigation of piles, disposed of in existing slurry lagoons, or be treated adequately before discharge. The drainage and collection system has to be able to handle heavy rainfall.<sup>[59]</sup>

#### Standards

In order to determine whether certain packaging materials, i.e., plastics and papers, are compostable, standards

organizations, such as ASTM and ISO, have published their own series of standards for compostability and/or biodegradability of materials in different exposure environments. In general, these standards describe terminology and definitions, testing guidelines, procedures, conditions, significance, limits, and results interpretation. In this overview, the standards are separated into two groups, ASTM and ISO standards, as these are the two main standards organizations.

#### ASTM Standards

The current ASTM standards involving the compostability and biodegradability of a material can be categorized into three groups based on exposure environments: 1) composting, 2) anaerobic digestion and wastewater treatment, and 3) others (see Table 2). Only standards involving composting of plastics will be included in this overview and the discussion will mainly focus on standards for compostable plastics.

According to ASTM D6400,<sup>[7]</sup> to claim that a certain material is compostable (see Figure 8), it must meet requirements that include satisfactory disintegration, biodegradation, and terrestrial and aquatic safety in a controlled laboratory scale composting test.

In this test, described in guide D6002 (Tier 2)<sup>[60]</sup> and test method D5338,<sup>[24]</sup> the test materials are exposed to the compost mixture in closed vessels. At least 12 vessels must be used: 3 blanks, 3 negative controls such as LDPE, 3 positive controls such as cellulose, and 3 for the test material. CO<sub>2</sub>-free humidified air is supplied for a test period of no less than 45 or more than 180 d, at a constant temperature of 58 °C (thermophilic phase), or using a desired temperature profile (e.g., 35 °C for 1 d, 58 °C for 4 d, 50 °C for 23 d, and 35 °C for 2 d). The amount of carbon dioxide gas evolved is measured using either a cumulative method (titration method), or direct measurement from the exhaust air, using an infrared (IR) detector or gas chromatography (GC). Figure 9(a) and (b) shows systems for biodegradation evaluation by the cumulative method and by direct measurement, respectively.<sup>[61]</sup> At the end of the test period, if no more than 10% of the original dry weight is found to remain after sieving the final compost with a 2 mm sieve, then the test material shows satisfactory disintegration.

To achieve satisfactory biodegradation, the cumulative percentage of organic carbon converted into carbon dioxide gas, or mineralization, compared to the theoretical value for the test polymer must be at least 60% for a material containing a single polymer (homopolymer or random copolymer), and 90% for a material containing a block copolymer, segmented copolymer, blend, or low-molecular-weight additives.

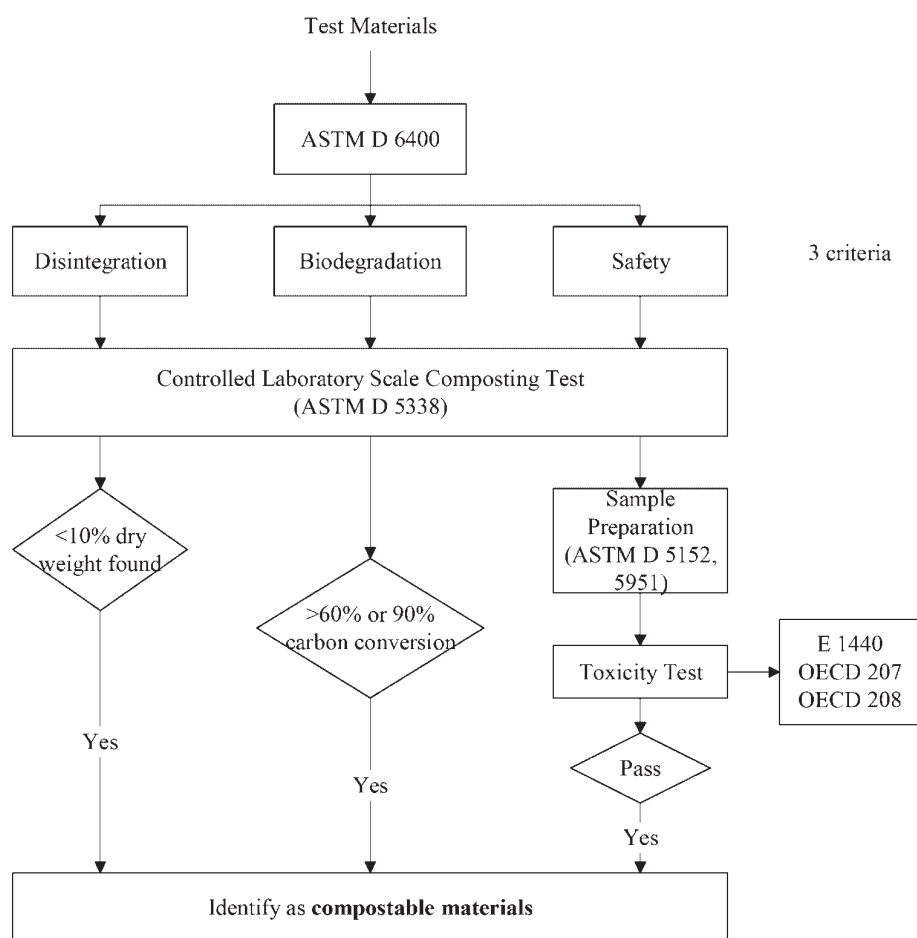
Table 2. List of current ASTM standards sorted by category.

Category	Standard
Composting environment	D6400 "Standard Specification for Compostable Plastics"
	D6002 "Standard Guide for Assessing the Compostability of Environmentally Degradable Plastics"
	D5338 "Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials Under Controlled Composting Conditions"
	D5988 "Standard Test Method for Determining Aerobic Biodegradation in Soil of Plastic Materials or Residual Plastic Materials After Composting"
	D5929 "Standard Test Method for Determining Biodegradability of Materials Exposed to Municipal Solid Waste Composting Conditions by Respirometry"
	D6954 "Standard Guide for Exposing and Testing Plastics that Degrade in the Environment by a Combination of Oxidation and Biodegradation"
	D6340 "Standard Test Methods for Determining Aerobic Biodegradation of Radiolabeled Plastic Materials in an Aqueous or Compost Environment"
Anaerobic digestion and wastewater treatment	D5210 "Standard Test Method for Determining the Anaerobic Biodegradation of Plastic Materials in Presence of Municipal Sewage sludge"
	D5271 "Standard Test Method for Determining the Aerobic Biodegradation of Plastic Materials in an Activated-Sludge-Wastewater-Treatment System"
	D5526 Standard for Determining Anaerobic Biodegradation of Plastic Materials Under Accelerated Landfill Conditions
	D5511 Standard Test Method for Determining Anaerobic Biodegradation of Plastic Materials Under High-Solids Anaerobic-Digestion Conditions
Other standards	D5951 "Standard Practice for Preparing Residual Solids Obtained After Biodegradability Standard Methods for Plastics in Solid Waste for Toxicity and Compost Quality Testing"
	D5975 "Standard Test Method for Determining the Stability of Compost by Measuring Oxygen Consumption"

For determination of terrestrial and aquatic safety, the concentration of heavy metal in plastic must be lower than 50% of the amount listed in 40CFR§503.13,<sup>[62]</sup> and the final compost must pass the toxicity test, including aquatic toxicity test with *Rotifer Brachionus* (Guide E 1440),<sup>[63]</sup> the plant germination with cress seed test, the plant growth test (OECD Guideline 208),<sup>[64]</sup> and the earthworm test (OECD Guideline 207).<sup>[27]</sup> In order to pass the toxicity test, the results from the compost that contains the test materials must have no significant differences compared to the

blank compost. Prior to the toxicity test, the final compost from the controlled laboratory scale composting test must be prepared in accordance with test method D5951.<sup>[65]</sup>

ASTM D6400 also defines biodegradable plastic as a degradable plastic in which the degradation results from the actions of microorganisms such as bacteria, fungi, and algae.<sup>[7]</sup> Therefore, based on this definition, for example, PLA, a commonly used biopolymer, would not qualify as a biodegradable material since the main degradation mechanism is hydrolysis. Another definition needing more



■ Figure 8. Compostable materials identification flow chart.

explanation is compostable plastic. D6400 defines this term without including the types of compost the plastic will be exposed to, or the time limit required for material to become fully degraded. This vague definition gives room for materials to claim they are compostable even if they will not compost as fast as natural materials such as yard trimmings, food wastes, and kraft paper.

Test method D5988<sup>[66]</sup> or the 'soil contact test', as described in guide D6002 Tier 1, can be used as a rapid screening test prior to test method D5338. In this test, the sample and reference materials are mixed with a soil mixture in air sealed vessels, such as desiccators, with each vessel containing only one test material. The test vessels are stored in the dark at 21 °C (mesophilic phase) for 30–60 d. The amount of evolved carbon dioxide is quantified by titration. A positive result, which means more than 60 or 90% of the total organic carbon is converted into carbon dioxide (depending on the polymer composition as described above), indicates that the test material will also biodegrade in the composting environment, which

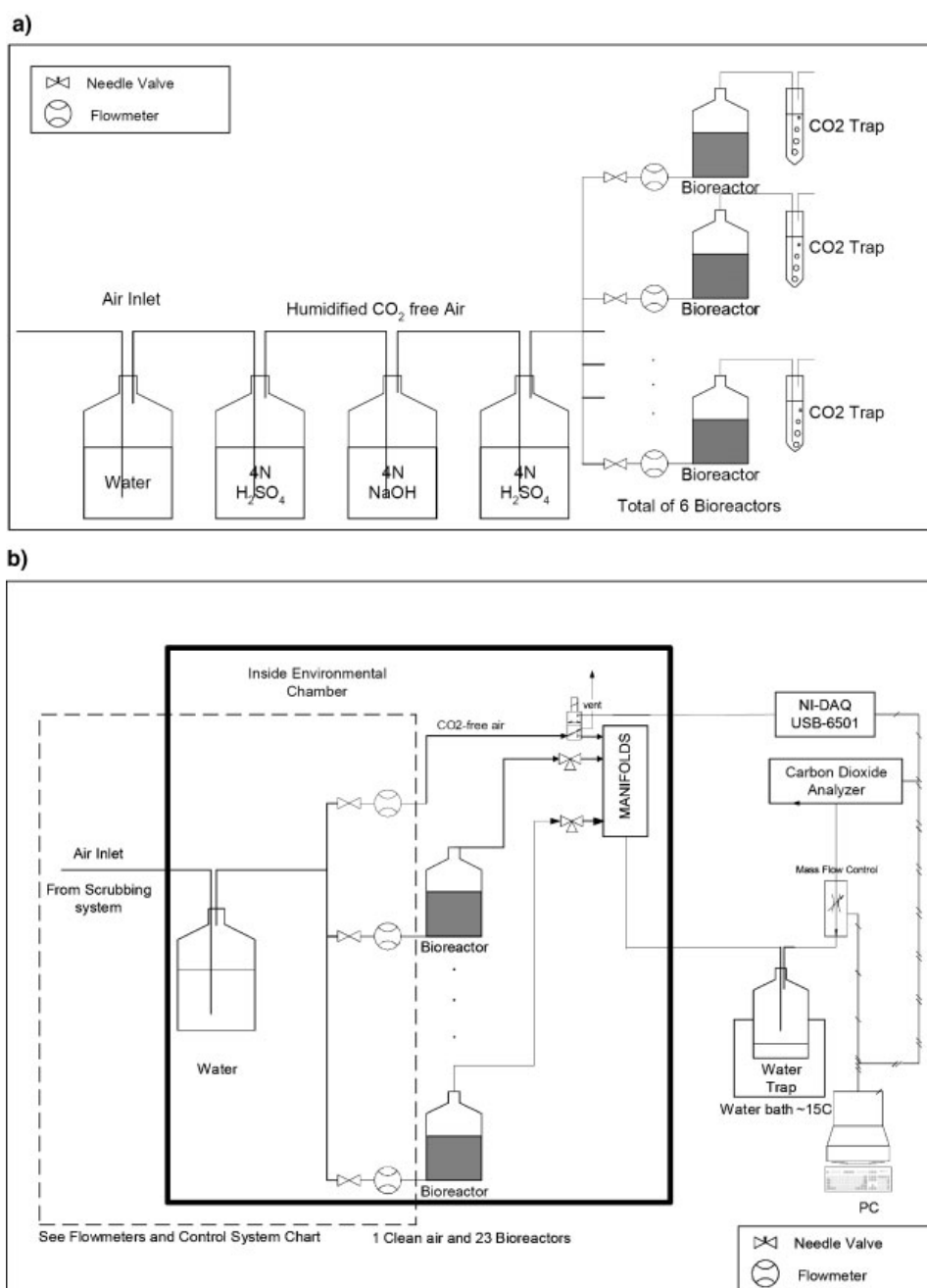
has a higher temperature. However, a negative result should be confirmed by test method D5338.

There are some standards that involve exposing materials to a compost environment that are not listed in specification D6400 for compostable materials identification, e.g., test method D5929,<sup>[67]</sup> and guide D6954.<sup>[68]</sup> In test method D5929,<sup>[67]</sup> the biodegradability of the test material exposed to the MSW composting condition (40 °C) is determined by measuring the oxygen uptake and carbon dioxide production from each reactor for a test period of 45 d. The percentage of biodegradation is then calculated by dividing the total cumulative oxygen uptake and carbon dioxide production by the theoretical value. Guide D6954<sup>[68]</sup> is a tier-based framework, similarly to D6002, to compare and rank the degree of degradation of polymers by thermal- and photo-oxidation com-

combined with biodegradation in disposal environments such as soil, landfill, and compost with other tested polymers chosen for that application. Tier 1 involves exposing the test material to thermal- or photo-oxidation conditions, based on its intended application. In tier 2, the residual fragments from tier 1 are subjected to a 'biometer test' such as D5338 or D5988, to measure the carbon dioxide evolution in the simulated disposal environment; soil (20–30 °C), landfill (20–35 °C), or compost (30–65 °C). The 60 and 90% organic carbon conversion described in specification D6400 also applies to this guide. In tier 3, the residue from the biometer test is subjected to toxicity tests, which are similar to those listed in guide D6002 tier 2.

### European and ISO Standards

There are only a few European and ISO standards that involve packaging and composting environments. The specification, test scheme, and guidelines are detailed in EN 13432.<sup>[8]</sup> Unlike the ASTM standards, this standard can



■ Figure 9. (a) Accumulative and (b) direct method to measure biodegradation.<sup>[61]</sup>

be applied to any packaging or packaging component, and is not limited to plastic materials. Moreover, instead of three criteria for plastic compostability, there are four criteria in the EN 13432 standard: 1) characterization, 2) biodegradability, 3) disintegration, and 4) compost quality or ecotoxicity. However, these four criteria cover the same scope as ASTM's three criteria.

In characterization, the packaging materials are analyzed to determine the composition, the presence of hazardous substances (e.g., heavy metals), organic carbon content, and total dry and volatile solids. To pass this criterion, the packaging material must have those values within specifications listed in Annex A.1 of EN 13432. For example, packaging, packaging materials, and packaging

**Table 3.** Maximum heavy metal content of packaging material and whole packaging from EN 13432 Annex A.1.<sup>[8]</sup>

Element	Content in dry substance
	mg · kg <sup>-1</sup>
Zn	150
Cu	50
Ni	25.0
Cd	0.5
Pb	50
Hg	0.5
Cr	50
Mo	1
Se	0.75
As	5
F	100

components should contain at least 50% of volatile solids, and the concentration of heavy metals should not exceed the values listed in Table 3. 'Volatile solids' means the materials that become volatile at high temperatures; a temperature of 550 ± 50 °C is used for an ignition test as described by ASTM D5338<sup>[24]</sup> and the American Public Health Association (APHA) standards 2540 E.<sup>[69]</sup>

The biodegradation test is described in ISO 14855,<sup>[9]</sup> and is similar to the test method in ASTM D5338, with a few differences. First, the ISO test method does not require the negative control vessels; therefore, only 9 vessels are required instead of 12. Second, ISO 14855 also includes the determination of percentage of biodegradation based on weight loss as an optional result to support the value determined from carbon dioxide evolution. Third, the acceptance level of percentage of biodegradation of the test material is at least 90% in total or 90% of the maximum degradation of the reference material after a plateau stage for both reference and test materials has been reached. For disintegration, the European and ISO standard suggest testing the materials in controlled pilot-scale and full-scale tests, as described in ISO 16929,<sup>[70]</sup> instead of using the controlled laboratory-scale test in ASTM D6400. But the rest is similar, i.e., the final compost is screened with a 2 mm screen, and the material needs to pass the disintegration criterion (i.e., no more than 10% of the original dry weight is recovered after 12 weeks of composting).

For the compost quality or ecotoxicity test, physical and chemical parameters such as density, total dry and volatile solids, salt content, and pH, have to be determined to show that the test packaging does or does not have negative effects on the compost quality. Only the plant growth test, based on OECD guideline 208,<sup>[64]</sup> is included in EN 13432 for ecotoxicity. The results (germination numbers and

plant biomass) of the compost with test material and the blank compost are compared. Figure 10 shows a detailed flowchart of the evaluation of organic recoverability of packaging according to EN 13432.

As shown in Figure 8 and 10, the procedure to have any package certified as 'compostable' is very elaborate. It involves not only the package passing the test method ASTM 5338<sup>[24]</sup> or ISO 14855,<sup>[9]</sup> but also meeting various other requirements, such as passing the disintegration test, having levels of heavy metals within limits, and passing the plant growth test by having no significant difference between the compost containing test material and the blank compost. For example, Figure 11 shows the percentage of mineralization of the PLA bottles previously tested in the compost facility and shown in Figure 5, compared with PET bottles (negative control) and corn starch (positive control), according to ASTM D5338 and ISO 14855.<sup>[61]</sup> This test will comply with the first and second requirements of ASTM D6400 and EN 13432, characterization and biodegradability. However, this test does not certify that the material is compostable according to these standards. Further studies that assess the complete disintegration and the compost quality or ecotoxicity of the bottles are required. Therefore, the PLA bottle could not be labeled as compostable just by passing ASTM D5338 and ISO 14855.

## Labeling and Certification

Currently, there is confusion about conventional plastics and biodegradable and compostable plastics throughout the U. S., since they are hardly physically distinguishable.<sup>[71]</sup> To succeed in recovering these materials and properly composting them, there must be a labeling system that separates them from conventional materials. Organizations such as the Biodegradable Products Institute (BPI) located in New York City; the U. S. Composting Council (USCC), located in Holbrook, NY; and DIN CERTCO, the certification organization of DIN, the German Institute for Standardization, offer certification programs that award a compostable logo to approved products.

In order to claim or label a product or package as compostable, or biodegradable, there should be reliable scientific evidence to support this claim.<sup>[72,73]</sup> Packages that are compostable in institutional facilities may not be compostable in home composting, because of different composting conditions, such as the waste mixture, moisture content, and temperature. Therefore, the claim must be clarified enough to avoid deception, especially considering the limited availability of compost facilities.<sup>[72]</sup> These are reasons for certification; therefore, concrete evidence must be submitted to organizations to have any products certified.

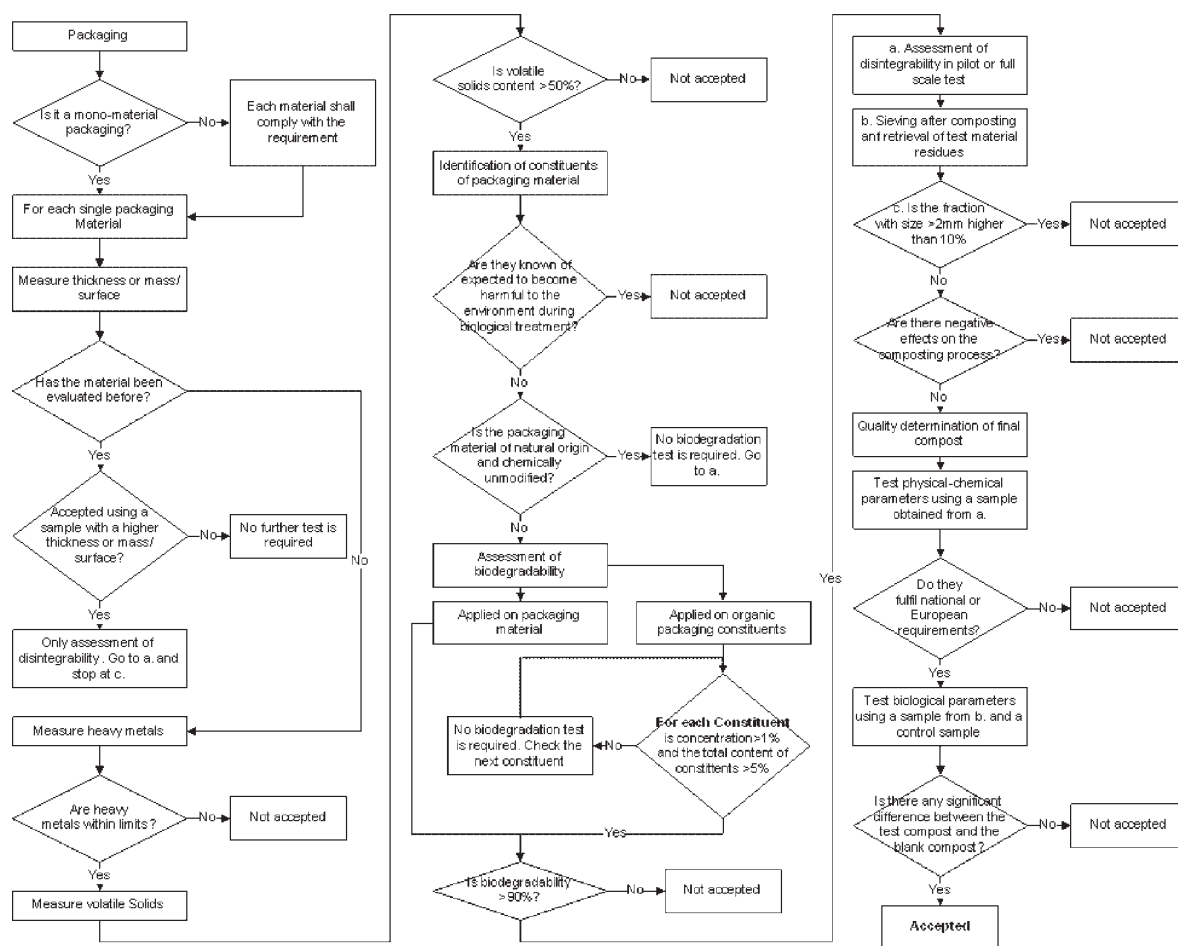


Figure 10. Flowchart of evaluation of organic recoverability of packaging based on EN 13432 standard.<sup>[8]</sup>

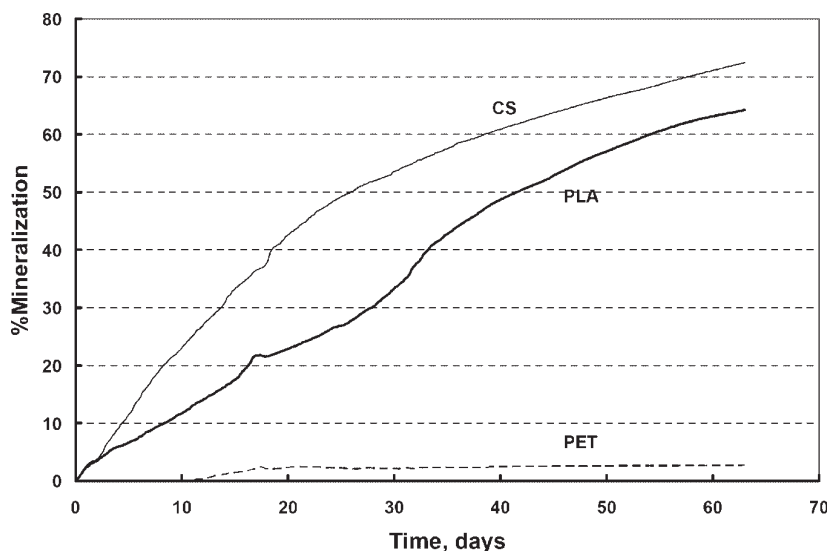


Figure 11. Percentage of mineralization of PLA and PET bottles and corn starch measured according ASTM D5338<sup>[24]</sup> and ISO 14855.<sup>[9]</sup>

Packaging manufacturers can have their products certified as ‘compostable’, which can be used as a marketing advantage. In addition, composting facilities can be assured that certified products are definitely compostable. Therefore, certification is the first step to have compostable packages accepted by composting facilities. Two of the most recognized certification organizations are BPI and DIN CERTCO. BPI, in cooperation with the USCC, uses the ASTM specifications D6400<sup>[7]</sup> and D6868<sup>[74]</sup> “Standard Specification for Biodegradable Plastics Used as Coatings on Paper and Other Compostable Substrates”.<sup>[8]</sup> The compostable logo, see Figure 12(a), is given to products that are compliant with ASTM specifications based on testing results from any approved

laboratory. A list of the approved laboratories can be found online at the BPI website: <http://bpiworld.org/BPI-Public/Program/Labs.html>. Similarly, DIN CERTCO certifies compostable products made from biodegradable materials based on laboratory tests of either ASTM specification D6400,<sup>[7]</sup> or the European standard DIN EN 13432,<sup>[8]</sup> and the 'compostable' logo, see Figure 12(b), is awarded to products that meet one of these standards.<sup>[75]</sup> Many other organizations also certify compostable materials based on ASTM D6400,<sup>[7]</sup> DIN EN 13432,<sup>[8]</sup> or both. For example, AIB Vincotte (AV), located in Belgium, awards the 'OK compost' logo, see Figure 12(c). Other certification bodies award certificates (not compostable labels) to products that meet ASTM, ISO, or CEN standards, similar to the ISO 9000 series certification. For example, SGS offers biodegradability and ecotoxicity testing based on ISO standards.

Currently, approved BPI and DIN CERTCO compostable products include compostable bags and films; packaging, such as water bottles, ovenable and microwavable trays; dishes and bowls; disposable utensils; and resins, such as Ecoflex from BASF, PLA from NatureWorks LLC, and Mater-Bi from Novamont.<sup>[8,75]</sup>

In 2006, Assembly Bill No. 2147 "Solid waste: Compostable plastic food and beverage containers" was intro-

duced by Harman in California. This bill prohibits selling plastic food and beverage containers labeled 'degradable', 'biodegradable', or 'compostable' unless the containers meet current ASTM standards,<sup>[76]</sup> in contrast to the existing law that applies only to plastic bags. However, the bill does not specify the ASTM standards, and it does not address which standards the packages have to comply with, for example D5338 or D6400. The purpose of the bill is to stop food and beverage packaging manufacturers or distributors from using mislabeling, because there has been erroneous use of the words 'degradable', 'biodegradable', and 'compostable' in marketing. Therefore, there must be a system to label the packages that is reliable and scientifically based.

### Life Cycle Analysis

As discussed earlier, LCA is an evaluation technique that compares the performance of alternative systems and products; and quantifies the environmental consequences of a product, system, or process over its entire life. As delineated in ASTM D7075,<sup>[12]</sup> the LCA methodology for biobased products involves distinct stages such as goal setting, inventory analysis, impact assessment, and interpretation. Goal setting defines the reasons for and scope of the study, including its breadth and depth. The inventory analysis identifies and quantifies the environmental inputs (water, energy, raw material, land, and other resources) and outputs (releases to air, land, and water) associated with the product over its entire life cycle. Impact assessment characterizes the inventory input-output flows in relation to a set of environmental impacts (such as resource depletion, global warming, ozone depletion, human toxicity, ecotoxicity, photochemical oxidant, acidification, eutrophication, and degradation of ecosystems and landscapes). The final interpretation step combines the environmental impacts and describes the results in a manner and in accordance with the goals of the LCA study.<sup>[13]</sup> The practice stated in ASTM D7075 is in accordance with the terminology and concepts used in ISO Standards 14040–14043.<sup>[77–80]</sup>

The waste management stage for the compostable packages may include composting, combustion, landfilling or recycling. The final disposal system has an important role in the overall ecobalance, especially for biodegradable materials. If biobased materials are disposed through composting, and the compost is further used in land application, then significant emission and energy credits can accrue, because of the value of the compost to sustainable agriculture. Impact factors emphasized in earlier LCA studies of biodegradable packaging include eutrophication, ecotoxicity, and land use.<sup>[81]</sup>

According to the EPA, the evaluation of greenhouse gas emissions of a polymer system should include analysis of

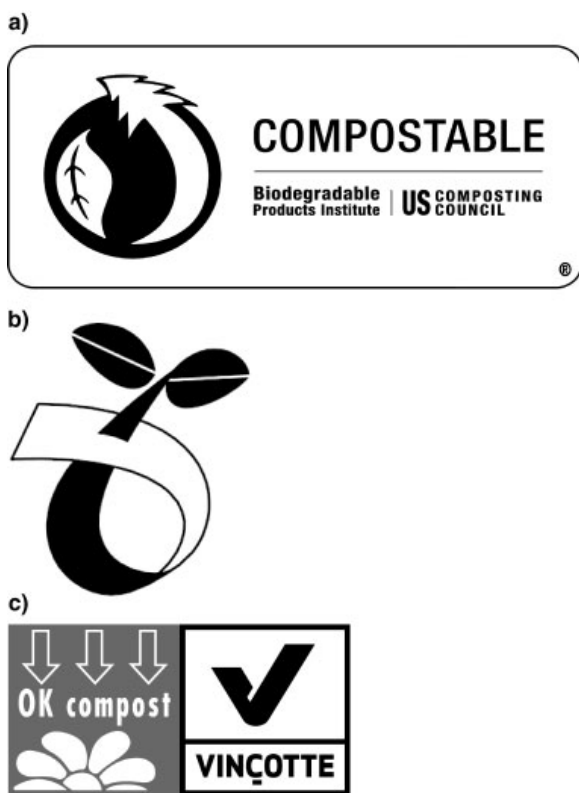


Figure 12. (a) BPI compostable logo, (b) DIN CERTCO compostable logo and (c) OK compost logo.

three factors: 1) greenhouse gas emissions throughout the life cycle of the polymer, including utility emissions and emissions from the disposal option; 2) the extent to which carbon sinks are affected by manufacturing and disposing of the material; and 3) the extent to which the management option recovers energy that can be used to replace electricity, thus reducing utility greenhouse gas emissions. According to Bohlmann,<sup>[81]</sup> there is considerable uncertainty in estimating the impact of biodegradable polymers such as PLA on emissions of greenhouse gases, and few studies have been published that address greenhouse gas emissions and carbon sequestration associated with landfilling.

LCA studies have been done on composting at the University of New South Wales, Australia. However, they reported some limitations of LCA as a tool to evaluate the total environmental impact assessment of a compost operation, since a number of reductions in agricultural inputs (such as fertilizers and water) and improvement in soil conditions could not be evaluated because of the unavailability of required characterization or equivalency factors.<sup>[82]</sup>

Another LCA study evaluated the environmental impacts of solid waste management alternatives, and concluded that if organic waste is diverted from landfills to composting, there is a reduction in the energy recovery and greenhouse gas emission benefits of the waste management system. The composting process increases emissions and uses energy. Again, in this study; the environmental consequences of composting could not be characterized completely because of lack of data. Offsets could include reduced fertilizer use, conservation of nutrients in compost-amended soil, less irrigation, reduced pesticide application, avoided harvest and transportation of peat, or avoided manufacture of erosion control products.<sup>[83]</sup>

Komilis and Ham developed a life cycle inventory (LCI) model for municipal solid waste composting and yard waste facilities.<sup>[84]</sup> Their model considers the production of compost as a high and low value product, and was based on laboratory experiments to determine selected emissions that were not available. The model considers three organic streams: food waste, mixed paper, and yard waste. They found that the odor control system and the building were the largest capital cost (around 77% of the total capital cost) for these types of operation. In addition, they reported that more than 90% of the emitted CO<sub>2</sub> was a result of solid waste decomposition. Further research that characterized the emissions determined that indicators are necessary in order to systematically evaluate and compare composting facilities.

## Conclusion

As new biopolymers obtained from renewable resources such as polylactide, and poly(hydroxybutyrate) are increa-

singly becoming available for food, medical, and consumer goods packaging applications, disposal of these polymers through composting is an available alternative. However, until now the main focus of companies promoting these biomaterials is the claim that they are obtained from environmentally friendly renewable resources and reduce petroleum consumption (even though only about 5% of refinery production goes to chemical products, including polymers). Since recycling and composting programs for these materials are generally not available, these 'green' materials mostly end up in landfill, along with many other packaging materials. Therefore, a better approach to the disposal of these new biomaterials is needed. In addition, state or federal regulations are necessary to avoid improper compostability claims.

Although recycling could be energetically more favorable than composting for many of these new biopolymers, it may not be practical because of sorting and cleaning requirements. A viable alternative is composting. However, since at present there is no system in place for the collection and composting of these materials, their main benefit is just green marketing based on pseudo-environmental benefits. The risky point of these claims is that we have really created a new packaging waste problem, rather than a sustainable packaging solution. Compostable packages can be a valuable alternative if we are willing to formally address the challenge of clearly understanding the cradle-to-grave life of these materials. Including compostable polymers in existing food, manure, or yard waste composting facilities is a promising approach. Canada and Germany are among the countries in the forefront of this initiative, positioning them to take full advantage of adopting these new materials.

Acknowledgements: T. K. thanks the project *GREEN* for financial support. The authors thank *Ramani Narayan* for useful comments and suggestions.

Received: July 28, 2006; Revised: November 1, 2006; Accepted: November 7, 2006; DOI: 10.1002/mabi.200600168

Keywords: biodegradation; biopolymers; compostability; degradation; packaging

- [1] EPA, "Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2003", Environmental Protection Agency, Washington, DC 2003, Available at <http://www.epa.gov/garbage/pubs/msw05rpt.pdf>. Access date 03/04/06.
- [2] PIRA, "Study on the Implementation of Directive 94/62/EC on Packaging and Packaging Waste Options to Strengthen Prevention and Re-Use of Packaging", 2005. Available at [http://europa.eu.int/comm/environment/waste/studies/packaging/050224\\_final\\_report.pdf](http://europa.eu.int/comm/environment/waste/studies/packaging/050224_final_report.pdf). Access date 03/30/2006.
- [3] B. Alliance, "Packaging Waste in Australia: An Overview", 2004. Available at <http://www.boomerangalliance.org/>

- 000\_files/28\_container\_deposits.pdf. Access date 03/30/2006.
- [4] J. A. Biernbaum, A. Fogiel, "Compost Production and Use", in: Upper Midwest Organic Farming Conference, La Crosse, WI 2004.
- [5] R. Rynk, "On-Farm Composting Handbook", Northeast Regional Agricultural Engineering Service, Ithaca, NY 1992.
- [6] A. Gopferich, "Mechanisms of Polymer Degradation and Elimination", in: *Handbook of Biodegradable Polymers*, A. J. Domb, A. Kost, D. M. Wiseman, Eds., Hardwood Academic, Montreux 1997, pp. 451–471.
- [7] ASTM. "D6400-04. Standard Specification for Compostable Plastics", ASTM, West Conshohocken, PA 2004.
- [8] European Committee for Standardization. "EN 13432. Packaging – Requirements for Packaging Recoverable Through Composting And Biodegradation-Test Scheme And Evaluation Criteria For The Final Acceptance Of Packaging, European Standard", European Committee for Standardization, Brussels, Belgium 2000.
- [9] ISO. "14855:1999. Determination Of The Ultimate Aerobic Biodegradability And Disintegration Of Plastic Materials Under Controlled Composting Conditions—Method By Analysis Of Evolved Carbon Dioxide", ISO, Geneva, Switzerland 1999.
- [10] SF Recycling, "Compost and Green Waste Recycling Program". Available at [http://www.sfrecycling.com/sf\\_green\\_toter.htm](http://www.sfrecycling.com/sf_green_toter.htm). Access date 04/12/2006.
- [11] C. Kunzler, *Biocycle* **2001**, 42, 30.
- [12] ASTM. "D7075-04. Standard Practice for Evaluating and Reporting Environmental Performance of Biobased Products", ASTM, West Conshohocken, PA 2004.
- [13] R. Narayan, "Drivers And Rationale For Use Of Biobased Materials Based On Life Cycle Assessment (LCA)", in: Global Plastics Environmental Conference, Atlanta 2004.
- [14] T. Chandra, R. Rustgi, *Prog. Polym. Sci.* **1998**, 23, 1273.
- [15] W. Amass, A. Amass, B. Tighe, *Polym. Int.* **1998**, 47, 89.
- [16] S. Matsumura, N. Tomizawa, A. Toki, K. Nishikawa, K. Toshima, *Macromolecules* **1999**, 32, 7753.
- [17] R. Auras, B. Harte, S. E. Selke, *Macromol. Biosci.* **2004**, 4, 835.
- [18] S. E. M. Selke, "Plastics Recycling and Biodegradable Plastics", in: *Modern Plastic Handbook*, C. A. Harper, Ed., Mc Graw Hill, New York 2001, p. 107.
- [19] A.-C. Albertsson, "Biodegradation of Polymers", in: *Handbook of Polymer Degradation*, M. B. A. S. Halim Hamid, A. G. Maadhah, Eds., Marcel Dekker, New York 2000, pp. 345–363.
- [20] E. S. Stevens, *Biocycle* **2003**, 24, 24.
- [21] D. E. Henton, P. Gruber, J. Lunt, J. Randall, "Polylactic Acid Technology", in: *Natural Fibers, Biopolymers, and Biocomposites*, A. K. Mohanty, M. Misra, L. T. Drzal, Eds., Taylor & Francis, Boca Raton, FL 2005, pp. 527–577.
- [22] G. H. Kai-Lai, A. L. Pometto, III, P. N. Hinz, *J. Environ. Polym. Degrad.* **1999**, 7, 83.
- [23] G. H. Kai-Lai, A. L. Pometto, III, P. N. Hinz, A. Gadea-Rivas, J. A. Briceño, A. Rojas, *J. Environ. Polym. Degrad.* **1999**, 7, 173.
- [24] ASTM. "D5338-98<sup>1</sup>. Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials Under Controlled Composting Conditions", ASTM, West Conshohocken, PA 1998.
- [25] S. Gartiser, M. Wallrabenstein, G. Stiene, *J. Environ. Polym. Degrad.* **1998**, 6, 159.
- [26] ASTM. "D5511-94 Standard Test Method for Determining Anaerobic Biodegradation of Plastic Materials Under High-Solids Anaerobic-Digestion Conditions", ASTM, West Conshohocken, PA 1994.
- [27] ISO. "14853:2005(E). Plastics—Determination Of Ultimate Anaerobic Biodegradation Of Plastic Materials In An Aqueous System-Method By Measurement Of Biogas Production", ISO, Geneva Switzerland 2005.
- [28] X. Zhang, U. P. Wyss, D. Pichora, M. F. A. Goosen, *J. Bioactive, Compat. Polym.* **1994**, 9, 80.
- [29] E. Chiellini, A. Corti, *Macromol. Symp.* **2003**, 197, 381.
- [30] EPA, "Composting Yard Trimmings And Municipal Solid Wastes, Solid Waste And Emergency Response", Environmental Protection Agency 1994. Available at <http://www.epa.gov/epaoswer/non-hw/compost/cytmsw.pdf>. Access date 03/06/2006.
- [31] EPA, "Composting: Facts and Figures", EPA 2006. Available at <http://www.epa.gov/msw/compost.htm>. Access date 03/30/2006.
- [32] S. Antler, *BioCycle* **2005**, 46, 36.
- [33] L. Marmo, "Biowaste Management In EU And Future Perspectives", European commission DG environment 2004. Available at [http://webrsv2.tekes.fi/opencms/opencms/OhjelmaPortaali/Kaynnissa/Streams/fi/Dokumenttiarkisto/Viestinta\\_ja\\_aktivointi/Seminaarit/2004/25-5-2004/3-Biowaste\\_management.pdf](http://webrsv2.tekes.fi/opencms/opencms/OhjelmaPortaali/Kaynnissa/Streams/fi/Dokumenttiarkisto/Viestinta_ja_aktivointi/Seminaarit/2004/25-5-2004/3-Biowaste_management.pdf). Access date 03/25/2006.
- [34] M. Jackson, *Biocycle* **2000**, 41, 64.
- [35] M. Chino, *Biocycle* **2001**, 42, 61.
- [36] M. Hampton, "Food Waste Composting", University of Florida. Available at [http://www.cra-recycle.org/CCC/education-training/2Day%20Presentations/7\\_Ozores\\_Food%20Waste%20Composting.pdf](http://www.cra-recycle.org/CCC/education-training/2Day%20Presentations/7_Ozores_Food%20Waste%20Composting.pdf). Access date 03/25/2006.
- [37] N. Goldstein, *BioCycle* **2005**, 46, 19.
- [38] N. Goldstein, *BioCycle* **2005**, 46, 20.
- [39] SF Recycling, "Compost and Green Waste Recycling Program", <http://www.sunsetscavenger.com/composting.htm>. Access date: 03/25/06.
- [40] J. Wolfe, *Biocycle* **2005**, 46, 51.
- [41] J. Wolfe, *BioCycle* **2006**, 47, 14.
- [42] G. Kale, R. Auras, S. P. Singh, "Evaluation of Compostability of Commercially Available Biodegradable Packages in Real Composting Conditions", in: American Institute of Chemical Engineers, Cincinnati, OH 2005.
- [43] G. Kale, R. Auras, S. P. Singh, "Comparison Of The Degradability Of Commercially Available Biodegradable Packages In Composting In Ambient Exposure Conditions", in: Global Plastics Environmental Conference, Atlanta, GA 2005.
- [44] G. Kale, R. Auras, S. P. Singh, *J. Polym. Environ.* **2006**, 14, 317.
- [45] G. Kale, R. Auras, S. P. Singh, *Packaging Technol. Sci.* **2006**, 19.
- [46] Y. Orhan, J. Hrenović, H. Büyükgüngör, *Acta Chim. Slov.* **2004**, 51, 579.
- [47] L. Otten, *Can. J. Civil Eng.* **2001**, 28, 124.
- [48] J. Barth, B. Kroeger, *Biocycle* **1998**, 39, 65.
- [49] V. Nelson, *Assessment of Windrow Turners*, Agtech Centre, 2002, [http://www1.agric.gov.ab.ca/\\$department/deptdocs.nsf/all/eng9938/\\$file/WindrowTurners.pdf?OpenElement](http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/eng9938/$file/WindrowTurners.pdf?OpenElement). Access date: 02/27/07.
- [50] L. Diaz, G. Savage, N. Goldstein, *Biocycle* **2005**, 46, 36.
- [51] N. Page, J. Leonard, G. Clark, *Biocycle* **2005**, 46, 57.
- [52] G. Savage, L. Diaz, N. Goldstein, *Biocycle* **2005**, 46, 55.
- [53] R. Sherman, *Biocycle* **2005**, 46, 45.
- [54] R. Rynk, *Biocycle* **2002**, 43, 38.
- [55] EPA, "Innovative Uses Of Compost: Composting Of Soils Contaminated By Explosives", United States Environmental Protection Agency 1997. Available at <http://www.epa.gov/epaoswer/non-hw/compost/explos.pdf>. Access date 03/30/2006.

- [56] EPA, "Innovative Uses Of Compost: Erosion Control, Turf Remediation And Landscaping", United States Environmental Protection Agency 1997. Available at <http://www.epa.gov/epaoswer/non-hw/compost/erosion.pdf>. Access date 03/30/2006.
- [57] "The Composting Process: Leachate Management", Composting Council of Canada. Available at [http://www.compost.org/pdf/sheet\\_6.PDF](http://www.compost.org/pdf/sheet_6.PDF). Access date 03/30/2006.
- [58] "Biodegradable Municipal Waste Management in Europe, Part3:TechnologyandMarketIssues", D. Tsotsos, Ed., European Environment Agency 2002. Available at [http://reports.eea.eu.int/topic\\_report\\_2001\\_15\\_Part3/en/part3](http://reports.eea.eu.int/topic_report_2001_15_Part3/en/part3). Access date 03/30/2006.
- [59] "On-farm Composting of Municipal and Commercial Organics as an Environmentally and Socially Sustainable Resource Recovery Scheme for Rural Communities", Environment Australia, Department of Environment and Heritage, Australian Government 2003. Available at <http://www.deh.gov.au/settlements/publications/waste/composting/scene.html>. Access date 04/01/2006.
- [60] ASTM. "D6002-96. Standard Guide for Assessing the Compostability of Environmentally Degradable Plastics", Reapproved, ASTM, West Conshohocken, PA 2002.
- [61] T. Kijchavengkul, R. Auras, M. Rubino, M. Ngouajio, R. Fernandez, *J. Polym. Test.* **2006**, 25, 1006.
- [62] ISO, "11266:1994(E). Soil Quality-Guidance On Laboratory Testing For Biodegradation Of Organic Chemicals In Soil Under Aerobic Conditions", ISO, Geneva, Switzerland 1994.
- [63] ISO, "14851:1999(E). Determination Of The Ultimate Aerobic Biodegradability Of Plastic Materials In An Aqueous Medium – Method By Measuring The Oxygen Demand In A Closed Respirometer", ISO, London, UK: 1999.
- [64] ISO, "14852:1999/Cor. 1:2005(E). Determination Of The Ultimate Aerobic Biodegradability Of Plastic Materials In An Aqueous Medium – Method By Analysis Of Evolved Carbon Dioxide", ISO, Geneva, Switzerland 2005.
- [65] ASTM. "D5951-96. Standard Practice for Preparing Residual Solids Obtained After Biodegradability Standard Methods for Plastics in Solid Waste for Toxicity and CompostQuality Testing", Reapproved, ASTM, West Conshohocken, PA 2002.
- [66] ASTM. "D5988-96. Standard Test Method for Determining Aerobic Biodegradation in Soil of Plastic Materials or Residual Plastic Materials After Composting", ASTM, West Conshohocken, PA 1996.
- [67] ASTM. "D5929-96. Standard Test Method for Determining Biodegradability of Materials Exposed to Municipal Solid Waste Composting Conditions by Compost Respirometry", Reapproved ASTM, West Conshohocken, PA 2004.
- [68] ASTM. "D6954-04. Standard Guide for Exposing and Testing Plastics that Degrade in the Environment by a Combination of Oxidation and Biodegradation", ASTM, West Conshohocken, PA 2004.
- [69] "Fixed and Volatile Solids Ignited at 550 °C", in: *Standards Methods for the Examination of Water and Wastewater*, American Public Health Association (APHA) standards, New York, NY 1987.
- [70] ISO, "16929:2002(E). Plastics – Determination Of The Degree Of Disintegration Of Plastic Materials Under Defined Composting Conditions In A Pilot-Scale Test", ISO, Geneva, Switzerland 2002.
- [71] E. Commission, "A Proposal for an Environmental Agreement in the Form of a Unilateral Industry Self-Commitment Concerning Biodegradable and Compostable Polymers", European Commission 2005. Available at [http://ec.europa.eu/enterprise/environment/index\\_home/emantool\\_indic\\_prodel\\_vappr/pol\\_doc/expl\\_memo.pdf](http://ec.europa.eu/enterprise/environment/index_home/emantool_indic_prodel_vappr/pol_doc/expl_memo.pdf). Access date 05/16/06.
- [72] FTC. "Complying with The Environmental Marketing Guides", May 2000, Division of Enforcement Federal Trade Commission, Washington, DC.
- [73] "Green Labeling: A Global Guide for Marketers and Manufacturers", Raymond Communications, Inc., MD, USA 2005.
- [74] ASTM, "D6868-03. Standard Specification for Biodegradable Plastics Used as Coatings on Paper and Other Compostable Substrates", ASTM, West Conshohocken, PA 2003.
- [75] DIN CERTCO, "The Compostability Mark of European Bioplastics and DINCERTCO", Available at [http://www.dincertco.de/en/about\\_us/our\\_marks\\_of\\_conformity/the\\_compostability\\_mark\\_of\\_european\\_bioplastics\\_and\\_din\\_certco.html](http://www.dincertco.de/en/about_us/our_marks_of_conformity/the_compostability_mark_of_european_bioplastics_and_din_certco.html). Access date 3/30/06, DIN, German Institute for Standardization, Cologne Germany.
- [76] "Harman Solid Waste: Compostable Plastic Food And Beverage Containers", (2006). Available at [http://www.leginfo.ca.gov/pub/bill/asm/ab\\_2101-2150/ab\\_2147\\_bill\\_20060221\\_introduced.pdf](http://www.leginfo.ca.gov/pub/bill/asm/ab_2101-2150/ab_2147_bill_20060221_introduced.pdf). Access date 03/30/06. California State Legislative, CA.
- [77] ISO. "14042:2000. Environmental Management – Life Cycle Assessment – Life Cycle Impact Assessment", ISO, Geneva, Switzerland 2000.
- [78] ISO. "14041:1998. Environmental Management – Life Cycle Assessment – Goal And Scope Definition And Inventory Analysis", ISO, Geneva, Switzerland 1998.
- [79] European Committee for Standardization. "ISO 14040:1997 Environmental Management – Life Cycle Assessment – Principles and Framework", EN, Brussels, Belgium 1997.
- [80] ISO, "14043:2000 Environmental management – Life Cycle Assessment – Life Cycle Interpretation", ISO, Geneva, Switzerland 2000.
- [81] G. M. Bohlmann, *Environ. Prog.* **2004**, 23, 342.
- [82] "Life Cycle Inventory And Life Cycle Assessment For Windrow Composting Systems", NSW, Department of health conservation, University of New South Wales, Sydney, Australia 2003.
- [83] M. A. Barlaz, P. O. Kaplan, S. R. Ranjithan, R. Rynk, *Biocycle* **2003**, 44, 52.
- [84] D. P. Komilis, R. K. Ham, *J. Environ. Eng.* **2004**, 130, 1390.