Nolan-ITU

Environment Australia

Biodegradable Plastics – Developments and Environmental Impacts

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EXECUTIVE SUMMARY

Biodegradable plastics are a new generation of polymers emerging on the Australian market. Biodegradable plastics have an expanding range of potential applications, and driven by the growing use of plastics in packaging and the perception that biodegradable plastics are ‘environmentally friendly’, their use is predicted to increase. However, issues are also emerging regarding the use of biodegradable plastics and their potential impacts on the environment and effects on established recycling systems and technologies.

Environment Australia, in consultation with the Plastics and Chemicals Industries Association (PACIA) has engaged Nolan-ITU, in association with ExcelPlas Australia, to undertake a national review of biodegradable plastics with the primary aim of identifying and characterising emerging environmental issues associated with biodegradable plastics to assist industry and the Commonwealth to develop initiatives to address these issues effectively.

Terms of Reference

The Terms of Reference of the review are to identify issues of relevance including the following:

1. Identify the various types and composition of biodegradable plastics available, and likely to be available in Australia.
2. Identify standards and test methods for biodegradable plastics in Australia.
3. Examine the range of disposal methods and identify the most frequent disposal option for each biodegradable plastic application at end of life.
4. Identify current technologies to avoid contamination and sort biodegradable plastics in Australia and overseas.
5. Describe and assess the current and potential future environmental impacts arising from the foreseeable increase in use of biodegradable plastics in various applications.
6. Identify possible and existing solutions to identified impacts and limitations.

Key Findings

The range of biodegradable plastics available include:

- Starch based products including thermoplastic starch, starch and synthetic aliphatic polyester blends, and starch and PVOH blends.
- Naturally produced polyesters including PVB, PHB and PHBH.
- Renewable resource polyesters such as PLA.
- Synthetic aliphatic polyesters including PCL and PBS.
- Aliphatic-aromatic (AAC) copolyesters.
- Hydro-biodegradable polyester such as modified PET.
- Water soluble polymer such as polyvinyl alcohol and ethylene vinyl alcohol.

- Photo-biodegradable plastics.
- Controlled degradation additive masterbatches.

There is a extensive range of potential applications. Some of these include:

- Film including overwrap, shopping bags, waste and bin liner bags, composting bags, mulch film, silage wrap, body bags/coffin liners, landfill covers, packaging – incl.O_2 & H_2O barriers, bait bags, nappy backing sheet, and cling wrap.
- Flushable sanitary products.
- Sheet and non woven packaging.
- Bottles.
- Liquid paper board.
- Planter boxes and fishing nets.
- Food service cups, cutlery, trays, and straws.
- Loose fill foam.

Whilst several biodegradable plastics are used for these applications in Europe, the current market penetration into Australia is low.

Several standards and test methods apply to biodegradable plastics internationally, however there are currently no Australian standards and test methods for biodegradable plastics. There is a need to establish Australian Standards that match the potential application areas and disposal environments in Australia.

The major potential disposal environments for biodegradable plastics are:

- composting facilities or soil burial;
- anaerobic digestion;
- wastewater treatment facilities;
- plastics reprocessing facilities;
- landfill;
- marine and freshwater environments; and
- general open environment as litter.

To a large extent, the nature of the biodegradable plastic application should dictate the disposal environment.

The risk of contamination by biodegradable plastics of conventional plastics which are currently recycled and reprocessed is a significant one, and the resultant effects on recyclate has the potential to undermine the growing confidence in recycled plastics. Effective methods for sorting biodegradable plastics would be needed in the event of their significant entry into the Australian market. Possible methods include near infra-red detection, which can be used in a positive sort system, or the use of a specific polymer code, and even colour, to differentiate biodegradable polymers from other recyclable polymers.

There are several identifiable environmental benefits that may potentially be derived from the use of biodegradable plastics compared to conventional petroleum-based plastics. These are:

- Compost derived in part from biodegradable plastics increases the soil organic content as well as water and nutrient retention, while reducing chemical inputs and suppressing plant disease.
- Biodegradable shopping and waste bags disposed of to landfill may increase the rate of organic waste degradation in landfills while enhancing methane harvesting potential and decreasing landfill space usage. Biodegradable landfill covers may also considerably extend landfill life.
- The energy required to synthesise and manufacture biodegradable plastics is generally much lower for most biodegradable plastics than for non-biodegradable plastics. The exception is PHA biopolymers which consume similar energy inputs to polyethylenes. New feedstock for PHA should lower the energy required for their production.
- Biodegradable plastics also offer important environmental benefits through, in many cases, the use of renewable energy resources and reduced greenhouse gas emissions.

Biodegradable plastics also pose some adverse environmental risks. These include:

- Pollution in waterways due to high BOD concentrations resulting from the breakdown of starch-based biodegradable plastic.
- Migration of plastic degradation by-products, (such as plastic residuals, additives and modifiers such as coupling agents, plasticisers, fillers, catalysts, dyes and pigments), via run-off and leachate from landfills and composting facilities to groundwater and surface water bodies.
- Trauma and death of marine species resulting from only partial or slow degradation of biodegradable plastic products in marine environments.
- Possible increase in the incidence of littering due to the belief that biodegradable plastics will disappear quickly.
- Soil and crop degradation resulting from the use of compost that may have unacceptably high organic and or metal contaminants derived from biogegradable plastic residuals, additives and modifiers such as coupling agents, plasticisers, fillers, catalysts, dyes and pigments.

Key Recommendations

For the successful introduction of degradable plastics into Australia it is essential that for any new application that the following are clearly identified:

- disposal route;
- appropriate recovery systems;
- processing infrastructure required; and
- the product has been tested against nationally agreed standards to ensure that the disposal route is appropriate and is environmentally sustainable.

For this to be achieved it will be necessary to establish a national framework for standards and testing. This can be based upon appropriate international standards. It is recommended that the Federal Government, through Environment Australia and in consultation with the plastics industry, take an initiating role in undertaking further research and developing these standards.

Further research focus areas include:

- Life-cycle assessment;
- Minimisation of the impacts on reprocessing;
- Determination of appropriate disposal methods; and
- Consumer education.

1 INTRODUCTION TO BIODEGRADABLE PLASTICS

The ‘biodegradability’ of plastics is dependent on the chemical structure of the material and on the constitution of the final product, not just on the raw materials used for its production. Therefore, biodegradable plastics can be based on natural or synthetic resins. Natural biodegradable plastics are based primarily on renewable resources (such as starch) and can be either naturally produced or synthesised from renewable resources. Non-renewable synthetic biodegradable plastics are petroleum-based. As any marketable plastic product must meet the performance requirements of its intended function, many natural biodegradable plastics are blended with synthetic polymers to produce plastics which meet these functional requirements.

Many polymers that are claimed to be ‘biodegradable’ are in fact ‘bioerodable’, ‘hydro-biodegradable’ or ‘photo-biodegradable’. These different polymer classes all come under the broader category of ‘environmentally degradable polymers’. **For the purpose of this document the term ‘biodegradable plastics’ shall imply ‘environmentally degradable plastics’.** The classes of biodegradable plastics considered, in terms of the degradation mechanism, are:

1) Biodegradable
2) Compostable
3) Hydro-biodegradable
4) Photo-biodegradable
5) Bioerodable

These definitions of degradation are used throughout the report to describe the degradation processes of the ‘biodegradable plastics’ currently available or under development. Definitions of these degradant mechanisms for different materials are provided below.

Biodegradable

The failure of early ‘biodegradable’ plastics to properly degrade led to the American Society of Testing and Materials (ASTM) creating definitions on what constitutes ‘biodegradability’. The ASTM definition, updated in 1994 (ASTM Standard D-5488-84d), has led to the establishment of labeling terminology for packaging materials.

The ASTM defines ‘biodegradable’ as:

“capable of undergoing decomposition into carbon dioxide, methane, water, inorganic compounds, or biomass in which the predominant mechanism is the enzymatic action of microorganisms, that can be measured by standardized tests, in a specified period of time, reflecting available disposal condition.”

Biodegredation is degradation caused by biological activity, particularly by enzyme action leading to significant changes in the materials chemical structure. In essence, biodegradable plastics should break down cleanly, in a defined time period, to simple molecules found in the environment such as carbon dioxide and water.

Biodegradation rates are highly dependent on the thickness and geometry of the fabricated articles. While rapid breakdown rates are often quoted these generally apply to thin films. Thick-walled articles such as plates, food trays and cutlery can take up to a year to biologically degrade.

Compostable

Compostable biodegradable plastics must be demonstrated to biodegrade and disintegrate in a compost system during the composting process (typically around 12 weeks at temperatures over 50°C). The compost must meet quality criteria such as heavy metal content, ecotoxicity, and no obvious distinguishable residues caused by the breakdown of the polymers. Compostable plastics are a subset of biodegradable plastics.

‘Compostable’ is defined by the ASTM as:

“capable of undergoing biological decomposition in a compost site as part of an available program, such that the plastic is not visually distinguishable and breaks down to carbon dioxide, water, inorganic compounds, and biomass, at a rate consistent with known compostable materials (e.g. cellulose).”

Hydro-biodegradable and Photo-biodegradable

Hydro-biodegradable and photo-biodegradabe polymers are broken down in a two-step process - an initial hydrolysis or photo-degradation stage, followed by further biodegradation. Single degradation phase ‘water-soluble’ and ‘photodegradable’ polymers also exist.

Bio-erodable

Many polymers that are claimed to be ‘biodegradable’ are in fact ‘bioerodable’ and degrade without the action of micro-organisms – at least initially. This is also known as abiotic disintegration, and may include processes such as dissolution in water, ‘oxidative embrittlement’ (heat ageing) or ‘photolytic embrittlement’ (UV ageing).

Sections 3, 4 and 5 outline the current biodegradable polymer types, technologies and developments. Many blends of these materials, particularly starch and polyester blends, are also considered. Biodegradable plastics that are intended to be ‘degradable in vivo’ (in the body, i.e. implants), are considered to be beyond the scope of this study.

2 BIODEGRADABLE STARCH-BASED POLYMERS

Starch is a linear polymer (polysaccaride) made up of repeating glucose groups linked by glucosidic linkages in the 1-4 carbon positions. The length of the starch chains will vary with plant source but in general the average length is between 500 and 2 000 glucose units. There are two major molecules in starch – amylose and amylopectin. The alpha linkage of amylose starch allows it to be flexible and digestible.

Starch-based biodegradable plastics may have starch contents ranging from 10% to greater than 90%. Starch based polymers can be based on crops such as corn (maize), wheat or potatoes. Starch content needs to exceed 60% before significant material breakdown occurs. As the starch content is increased, the polymer composites become more biodegradable and leave less recalcitrant residues. Often, starch-based polymers are blended with high-performance polymers (e.g. aliphatic polyesters and polyvinyl alcohols) to achieve the necessary performance properties for different applications.

Biodegradation of starch based polymers is a result of enzymatic attack at the glucosidic linkages between the sugar groups leading to a reduction in chain length and the splitting off of sugar units (monosaccharides, disaccharides and oligosaccharides) that are readily utilised in biochemical pathways.

At lower starch contents (less than 60%) the starch particles act as weak links in the plastic matrix and are sites for biological attack. This allows the polymer matrix to disintegrate into small fragments, but not for the entire polymer structure to actually bio-degrade.

There are several categories of biodegradable starch-based polymers including:

- Thermoplastic starch products;
- Starch synthetic aliphatic polyester blends;
- Starch PBS/PBSA polyester blends; and
- Starch PVOH Blends.

2.1 Thermoplastic Starch Products

Thermoplastic starch biodegradable plastics (TPS) have a starch (amylose) content greater than 70% and are based on gelatinised vegetable starch, and with the use of specific plasticising solvents, can produce thermoplastic materials with good performance properties and inherent biodegradability. Starch is typically plasticised, destructured, and/or blended with other materials to form useful mechanical properties. Importantly, such TPS compounds can be processed on existing plastics fabrication equipment.

High starch content plastics are highly hydrophilic and readily disintegrate on contact with water. This can be overcome through blending, as the starch has free hydroxyl groups which readily undergo a number of reactions such as acetylation, esterification and etherification.

Developments

The CRC for International Food Manufacture and Packaging Science Australia has developed its own version of TPS biodegradable plastics. These natural vegetable starch polymers have a amylose content greater than 70%.

Trials have been successfully performed using maize starch polymers as mulch film, and the material was found to perform as well as polyethylene film, with the added advantage that after harvest, the film can be simply ploughed into the soil. These natural starch polymers are now being commercialised through a new company called Plantic Technologies Ltd. based in Melbourne.

Applications

The applications of thermoplastic starch polymers are generally film, such as shopping bags, bread bags, bait bags, over wrap, ‘flushable’ sanitary product backing material, and mulch film.

Foam loose fill packaging and injected moulded products such as take-away containers are also potential applications. Foamed polystyrene can be substituted by starch foams that are readily biodegradable in some loose-fill packaging and foam tray applications.

Foamed starch loose-fills are rather easy products to produce and this area has become an early market for biodegradable plastics. During its preparation, raw starch is premixed with 25 to 50 weight percent water and fed into an extruder capable of imparting intensive shear and operating at high temperature (higher than the boiling point of water, i.e., 150-180ºC). Under these conditions of shear and temperature, starch breaks down, loses its crystallinity, and gets plasticised with water, resulting in a homogenous amorphous mass. When this gelatinised starch/water mixture exits the extruder, the water that is present in the mass at a temperature higher than its boiling point expands into steam due to a sudden drop in pressure, and the foam is formed. Generally a plasticiser (such as glycerol) and another polymer (such as polyvinyl alcohol) impart more reproducible properties to starch foam.

Degradation Mechanisms and Properties

Along with the biodegradation of the polymers by sugar molecules, certain TPS grades are also fully water soluble.

2.2 Starch Synthetic Aliphatic Polyester Blends

Blends of biodegradable synthetic aliphatic polyesters and starch are often used to produce high-quality sheets and films for packaging by flat-film extrusion using chill-roll casting or by blown film methods since it is difficult to cast films from 100% starch in a melted state. Approximately 50% of the synthetic polyester (at approximately $4.00/kg) can be replaced with natural polymers such as starch (at approximately $1.50/kg), leading to a significant reduction in cost. Furthermore, the polyesters can be modified by incorporating a functional group capable of reacting with natural starch polymers.

Developments

Lim et al. (1999) studied the properties of an aliphatic polyester blended with wheat starch. The polyester was synthesized from the poly-condensation of 1,4-butanediol and a mixture of adipic and succinic acids. The wheat starch–polyester blends were found to have melting points near that of the polyester alone. A plasticiser was added to the starch, making the blends more flexible and processable than the polyester itself. Plasticised blends were found to retain a high tensile strength and elongation at the break point, even at high concentrations of starch.

Blending starch with degradable synthetic aliphatic polyesters such as PLA and PCL has recently become a focus of biodegradable plastic development. Biodegradable plastics can be prepared by blending up to 45% starch with degradable PCL . This new material is not strong enough for most applications, as the melting temperature is only 60°C and it gets soft at temperatures above 40°C. These drawbacks greatly limit the applications of the starch-PCL blends. Table 2.1 details some starch-PCL polymers that are commercially available.

Table 2.1 – PCL Polymers (Commercially Available)

Polymer Type	Trade-name	Supplier	Origin
Starch-polycaprolactone (PCL) blends	Mater-Bi™	Novamont	Italy
	Bioflex™	Biotech	Germany

Applications

The applications for starch-synthetic aliphatic polyester blends include high-quality sheets and films for packaging and other film applications.

Several starch-based plastics are currently available on the Australian market. One of these is the ‘BioBag’, which is produced from the Novamont resin that has been around since 1994, and is made from corn starches in combination with fully biodegradable plastics or polylactic acid.

Degradation Mechanisms and Properties

The wheat starch-aliphatic polyester blend studied by Lim et al. (1999) demonstrated excellent biodegradability. Soil burial tests revealed complete biodegradation within eight weeks. The excellent properties exhibited by these blends make them ideal as commodity biodegradable plastics.

2.3 Starch and PBS/PBSA Polyester Blends

Other polyesters that are blended with starch to improve material mechanical properties are polybutylene succinate (PBS) or polybutylene succinate adipate (PBSA).

A small amount (5% by weight) of compatibiliser (maleic anhydride functionalised polyester) can be added to impart phase stability to these starch based polymer blends. At higher starch content (>60%), such sheets can become brittle. For this reason, plasticisers are often added to reduce the brittleness and improve flexibility.

Developments

Ratto et al.(1999) investigated the properties of PBSA and corn starch blends of varied compositions. PBSA is biodegradable, and exhibits excellent thermoplastic properties. The objective of the study was to obtain a mixture that maximised these properties while minimising cost. Corn starch is an inexpensive polysaccharide that was blended with PBSA at concentrations of 5–30% by weight for analysis. Tensile strength of the blends was lower than that of the polyester alone, but there was not a significant drop in strength with increasing starch content. In addition, melt temperature and processing properties were not appreciably affected by the starch content.

Applications

Starch and PBS or PBSA blends are used to produce biodegradable plastic sheet which can be thermoformed into products such as biscuit trays or film products.

Degradation Mechanisms and Properties

Ratto et al.(1999) investigated the blends the biodegradability properties of PBSA and corn starch blends by measuring CO_2 production in a soil burial test. Addition of only 5% starch showed a large reduction in half-life from that of the pure polyester. The half-life was found to decline with increasing starch content until a minimum 20% starch content was reached.

2.4 Starch-PVOH Blends

Polyvinyl alcohol (PVOH) is blended with starch to produce readily biodegradable plastics.

Developments

Propak, a Sydney-based company, produce loose-fill peanuts from a starch-PVOH blend (a grade of Mater-bi™) that exhibits water solubility in approximately 3 minutes. These expanded products have a closed cell pore structure and densities ranging from 0.01 to 0.1 g/cm^3. Table 2.2 details some of the starch-PVOH blends commercially available.

Table 2.2 – Starch-PVOH Blends Commercially Available

Polymer Type	Trade-name	Supplier	Origin
Starch-Polyvinyl Alcohol (PVOH) blends	Novon™	Chisso Corp	Japan
	Novon™	Warner Lambert	USA
	Mater-bi™	Novamont	Italy

Degradation Mechanisms and Properties

PVOH is readily water soluble, and the starch-PVOH blends are therefore degraded via hydrolysis and biodegradation of the sugar molecules.

3 BIODEGRADABLE POLYESTERS

Polyesters play a predominant role as biodegradable plastics due to their potentially hydrolysable ester bonds. As shown in Figure 3.1 below, the polyester family is made of two major groups – aliphatic (linear) polyesters and aromatic (aromatic rings) polyesters. Biodegradable polyesters which have been developed commercially and are in commercial development are as follows:

PHA – polyhydroxyalkanoates
PHH – polyhydroxyhexanoate
PLA – polylactic acid
PBS – polybutylene succinate
AAC – Aliphatic-Aromatic copolyesters
PBAT – polybutylene adipate/terephthalate

PHB – polyhydroxybutyrate
PHV - polyhydroxyvalerate
PCL – polycaprolactone
PBSA - polybutylene succinate adipate
PET – polyethylene terephthalate
PTMAT- polymethylene adipate/terephthalate

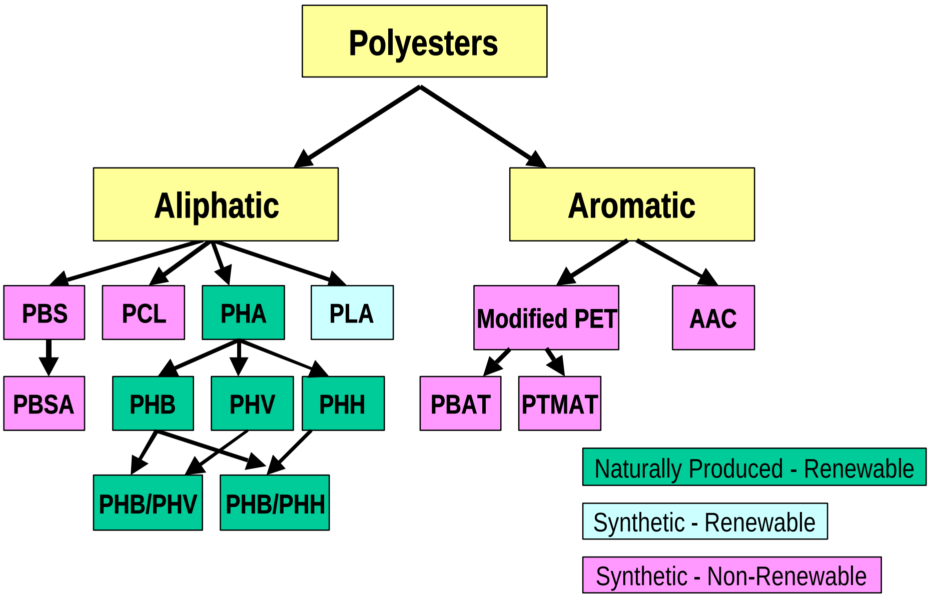

Figure 3.1 – Biodegradable Polyester Family

While aromatic polyesters such as PET exhibit excellent material properties, they prove to be almost totally resistant to microbial attack. Aliphatic polyesters on the other hand are readily biodegradable, but lack good mechanical properties that are critical for most applications. All polyesters degrade eventually, with hydrolysis (degradation induced by water) being the dominant mechanism.

Synthetic aliphatic polyesters are synthesised from diols and dicarboxylic acids via condensation polymerisation, and are known to be completely biodegradable in soil and water. These aliphatic polyesters are, however, much more expensive and lack mechanical strength compared with conventional plastics such as polyethylene.

Many of these polyesters are blended with starch based polymers for cost competitive biodegradable plastics applications. Aliphatic polyesters have better moisture resistance than starches, which have many hydroxyl groups.

The rate of soil degradation of various biodegradable plastics has been measured by Hoshino (2001). Poly-(3-hydroxy–butyrate-valerate) (PHB/PHV), PCL, PBS, PBSA, and PLA were evaluated in soil burial for 12 months and samples were collected every 3 months for the measurement of weight loss. The rate of degradation of PBSA, PHB/PHV and PCL was found to be similar; with the rate of PBS and PLA respectively slower.

3.1 PHA (Naturally Produced) Polyesters

Polyhydroxyalkanoates (PHAs) are aliphatic polyesters naturally produced via a microbial process on sugar-based medium, where they act as carbon and energy storage material in bacteria. They were the first biodegradable polyesters to be utilised in plastics. The two main members of the PHA family are polyhydroxybutyrate (PHB) and polyhydroxyvalerate (PHV).

Aliphatic polyesters such as PHAs, and more specifically homopolymers and copolymers of hydroxybutyric acid and hydroxyvaleric acid, have been proven to be readily biodegradable. Such polymers are actually synthesised by microbes, with the polymer accumulating in the microbes' cells during growth.

Developments

The most common commercial PHA consists of a copolymer PHB/PHV together with a plasticiser/softener (e.g. triacetine or estaflex) and inorganic additives such as titanium dioxide and calcium carbonate.

A major factor in the competition between PHAs and petroleum based plastics is in production costs. Opportunities exist however for obtaining cheaper raw materials that could reduce PHA production costs. Such raw materials include corn-steeped liquor, molasses and even activated sludge. These materials are relatively inexpensive nutrient sources for the bacteria that synthesise PHAs (Purushothaman, 2001).

The PHB homopolymer is a stiff and rather brittle polymer of high crystallinity, whose mechanical properties are not unlike those of polystyrene, though it is less brittle. PHB copolymers are preferred for general purposes as the degradation rate of PHB homopolymer is high at its normal melt processing temperature. PHB and its copolymers with PHV are melt-processable semi-crystalline thermoplastics made by biological fermentation from renewable carbohydrate feedstocks. They represent the first example of a true biodegradeable thermoplastic produced via a biotechnology process. No toxic by-products are known to result from PHB or PHV.

Applications

The applications of PHA are blow and injection-moulded bottles and plastic films. Such films are available in Australia under the Biopol™ trademark.

Degradation Mechanisms and Properties

PHAs are biodegradable via composting. Optimum conditions for the commercially available Biopol™ (PHA) degradation during a 10-week composting period were 60°C, 55% moisture, and C:N ratio of 18:1. Biopol™ reached close to a 100% degradation rate under these composting conditions. The aliphatic polyesters function like starch or cellulose to produce non-humic substances such as CO_2 and methane. These aliphatic polymers are suited to applications with short usage and high degradation rate requirements (Gallagher, 2001).

Shin et al. (1997) found that bacterial PHB/PHV (92/8 w/w) degraded nearly to completion within 20 days of cultivation by anaerobic digested sludge, while synthetic aliphatic polyesters such as PLA, PBS and PBSA did not degrade at all in 100 days. Cellophane, which was used as a control material, exhibited a similar degradation behavior to PHB/PHV. Under simulated landfill conditions, PHB/PHV degraded within 6 months. Synthetic aliphatic polyesters also showed significant weight losses through 1 year of cultivation. The acidic environment generated by the degradation of biodegradable food wastes which comprises approximately 34% of municipal solid waste seems to cause the weight loss of synthetic aliphatic polyesters.

3.2 PHBH (Naturally Produced) Polyesters

Poly-hydroxybutyrate-co-polyhydroxyhexanoates (PHBHs) resins are one of the newest type of naturally produced biodegradable polyesters. The PHBH resin is derived from carbon sources such as sucrose, fatty acids or molasses via a fermentation process.

These are ‘aliphatic-aliphatic’ copolyesters, as disctint from ‘aliphatic-aromatic’ copolyesters. Besides being completely biodegradable, they also exhibit barrier properties similar to those exhibited by ethylene vinyl alcohol (see Section 3.1.2). Procter & Gamble Co. researched the blending of these polymers to obtain the appropriate stiffness or flexibility.

Developments

They have been developed by Kaneka Corp. (a Japanese manufacturer) and marketed by Procter & Gamble Co. under the Nodax™ tradename.

Applications

The applications of the PHBH polymer are film, manufactured via casting or blowing methods. Potential applications are mono/multilayer film and non-woven paper packaging at costs comparable to traditional materials such as EVOH.

Degradation Mechanisms and Properties

PHBH resins biodegrade under aerobic as well as anaerobic conditions, and are digestible in hot water under alkaline conditions.

3.3 PLA (Renewable Resource) Polyesters

Polylactic acid (PLA) is a linear aliphatic polyester produced by poly-condensation of naturally produced lactic acid or by the catalytic ring opening of the lactide group. Lactic acid is produced (via starch fermentation) as a co-product of corn wet milling. The ester linkages in PLA are sensitive to both chemical hydrolysis and enzymatic chain cleavage.

PLA is often blended with starch to increase biodegradability and reduce costs. However, the brittleness of the starch-PLA blend is a major drawback in many applications. To remedy this limitation, a number of low molecular weight plasticisers such as glycerol, sorbitol and triethyl citrate are used.

PLA does not have full food contact approval due to its fermentation manufacturing method.

Developments

A number of companies produce PLA, such as Cargill Dow LLC. PLA produced by Cargill Dow was originally sold under the name EcoPLA, but now is known as NatureWorks PLA, which is actually a family of PLA polymers that can be used alone or blended with other natural-based polymers.

Table 3.1 details some of the other PLA biodegradable plastics that are commercially available.

Table 3.1 – PLA Polymers (Commercially Available)

Trade-name	Supplier	Origin
Lacea	Mitsui Toatsu	Japan
Lucty	Shimazu	Japan
NatureWorks	Cargill Dow	USA

Applications

The applications for PLA are thermoformed products such as drink cups, take-away food trays, containers and planter boxes. The material has good rigidity characteristics, allowing it to replace polystryene and PET in some applications.

Degradation Mechanisms and Properties

PLA is fully biodegradable when composted in a large-scale operation with temperatures of 60°C and above. The first stage of degradation of PLA (two weeks) is via hydrolysis to water soluble compounds and lactic acid. Rapid metabolisation of these products into CO_2, water and biomass by a variety of micro-organisms occurs after hydrolysis.

PLA does not biodegrade readily at temperatures less than 60°C due to its 'glass transition' temperature being close to 60°C.

3.4 PCL (Synthetic Aliphatic) Polyesters

Polycaprolactone (PCL) is a biodegradable synthetic aliphatic polyester made by the ring-opening polymerization of caprolactone. PCL has a low melting-point, between 58-60°C, low viscosity and is easy to process.

Developments

Until recently, PCL was not widely used in significant quantities for biodegradable polymer applications due to cost reasons. Recently however, cost barriers have been overcome by blending the PCL with corn-starch.

Table 3.2 details some of the various PCL biodegradable plastics that are commercially available.

Table 3.2 – PCL Polymers (Commercially Available)

Trade-name	Supplier	Origin
Tone	Union Carbide (UCC)	USA
CAPA	Solvay	Belgium
Placeel	Daicel Chemical Indus.	Japan

Applications

PCL is suited for use as food-contact foam trays, loose fill and film bags.

Degradation Mechanisms and Properties

Although not produced from renewable raw materials, PCL is fully biodegradable when composted. The low melting point of PCL makes the material suited for composting as a means of disposal, due to the temperatures obtained during composting routinely exceeding 60°C.

Rutkowska et. al. (2000) studied the influence of different processing additives on the biodegradation of PCL film in the compost with plant treatment active sludge. It was found that PCL without additives, completely degraded after six weeks in compost with activated sludge. The introduction of processing additives gave better tensile strength of the materials but made them less vulnerable to micro-organism attack.

The rate of marine biodegradation of PCL has been studied by Janik et. al. (1988) by measuring the tensile strength and percent weight loss over time in both seawater and a buffered salt solution. It was found that the weight loss, as a percent of total weight, decreased more rapidly in seawater than in the buffered salt solution. After eight weeks, the PCL in seawater was completely decomposed, whereas that in salt solution had lost only 20% of its weight. The same trend was seen for the tensile strength, where after eight weeks, the PCL in seawater was destroyed and that in buffered salt solution had decreased to roughly one-sixth its original value. It is therefore apparent that enzymes in the seawater solution assist to accelerate the biodegradation of PCL and other biodegradable plastics.

3.5 PBS (Synthetic Aliphatic) Polyesters

Polybutylene succinate (PBS) is a biodegradable synthetic aliphatic polyester with similar properties to PET. PBS is generally blended with other compounds, such as starch (TPS) and adipate copolymers (to form PBS-A), to make its use economical.

Developments

Table 3.3 shows some PBS and PBS-A biodegradable plastics which are commercially available.

Table 3.3 – PBS Polymers (Commercially Available)

Trade-name	Supplier	Origin
Bionelle	Showa Highpolymer	Japan
SkyGreen BDP	SK Polymers	Korea

Applications

PBS has excellent mechanical properties and can be applied to a range of end applications via conventional melt processing techniques. Applications include mulch film, packaging film, bags and ‘flushable’ hygiene products.

Degradation Mechanisms and Properties

PBS is hydro-biodegradable and begins to biodegrade via a hydrolysis mechanism. Hydrolysis occurs at the ester linkages and this results in a lowering of the polymer's molecular weight, allowing for further degradation by micro-organisms. Data from SK Chemicals (Korea), a leading manufacturer of PBS polymers, quotes a degradation rate of 1 month for 50% degradation for 40 micron thick film in garden soil.

3.6 AAC Copolyesters

Aliphatic-aromatic (AAC) copolyesters combine the biodegradable properties of aliphatic polyesters with the strength and performance properties of aromatic polyesters. This class of biodegradable plastics is seen by many to be the answer to making fully biodegradable plastics with property profiles similar to those of commodity polymers such as polyethylene. To reduce cost AACs are often blended with TPS.

Although AACs have obvious benefits, their market potential may be affected by legislation, such as that in Germany, which distinguishes between biodegradable plastics made from renewable resources and those, like AAC, which use basically the same raw materials as commodity plastics and petrochemicals. Currently in Germany, biodegradable plastics must contain greater than 50% renewable resources to be accepted.

Developments

The two main types of commercial AAC plastics are Ecoflex™ produced by BASF and Eastar Bio™ produced by Eastman. Under each trade name are a number of specific grades. Each grade of polymer has been designed with controlled branching and chain lengthening to match its particular application.

Applications

AACs come closer than any other biodegradable plastics to equalling the properties of low-density polyethylene, especially for blown film extrusion. AACs also can meet all the functional requirements for cling film such as transparency, flexibility and anti-fogging performance, and therefore this material has great promise for use in commercial food wrap for fruit and vegetables, with the added advantage of being compostable.

Degradation Mechanisms and Properties

Whilst being fossil fuel-based, AACs are biodegradable and compostable.

ACCs fully biodegrade to carbon dioxide, water and biomass. Typically, in an active microbial environment the polymer becomes invisible to the naked eye within 12 weeks. The extent and rate of biodegradation, apart from the inherent biodegradability of the polymer itself, depends on several environmental factors such as:

- moisture;
- temperature;
- surface area; and
- the manufacturing method of the finished product.

3.7 Modified PET

Modified PET (polyethylene tetraphalate) is PET which contains co-monomers, such as ether, amide or aliphatic monomers, that provide 'weak' linkages that are susceptible to biodegradation through hydrolysis. Depending on the application, up to three aliphatic monomers are incorporated into the PET structure. Typical modified PET materials include PBAT (polybutylene adipate/terephthalate) and PTMAT (polytetramethylene adipate/terephthalate).

Developments

DuPont have commercialised Biomax™ which is a hydro-biodegradable modified PET polyester. Certain Biomax™ grades also contain degradation promoters to provide tailored combinations of performance properties and degradation rates.

Applications

The options available for modified PET provide the opportunity to produce polymers which specifically match a range of application physical properties whilst maintaining the ability to adjust the degradation rate by the use of copolyesters.

Degradation Mechanisms and Properties

Modified PET is hydro-biodegradable, with a biodegradation steps following an initial hydrolysis stage. It contains weak linkages which create sites for microbial attack. The mechanism involves a combination of hydrolysis of the ester linkages and enzymatic attack on ether and amide bonds.

With modified PET it is possible to adjust and control degradation rates by varying the co-monomers used.

4 OTHER DEGRADABLE POLYMERS

4.1 Water Soluble Polymers

There are two main water soluble polymer types commercially available – polyvinyl alcohol (PVOH) and ethylene vinyl alcohol (EVOH).

4.1.1 Polyvinyl Alcohol (PVOH)

PVOH is a readily biodegradable, water soluble polymer. Conventional PVOH however, cannot be processed by traditional extrusion technologies since it decomposes close to its melting point of 230°C. Even partially hydrolysed grades, which melt at 180-190°C, undergo some decomposition during melt processing.

Developments

Until recently PVOH film was prepared by casting films from an aqueous solution. Recently however, new grades of PVOH have been commercialised which incorporate an internal plasticiser that are thereby extrudable and retain their water solubility.

Table 4.1 shows some of the PVOH biodegradable plastics which are commercially available.

Table 4.1 – PVOH Polymers (Commercially Available)

Trade-name	Supplier	Origin
Vinex	Air Products	USA
Elvanol	DuPont	USA
Poval	Kuraray Co.	Japan
Exceval	Kuraray Co.	Japan
Hi-Selon	Nippon Gohsei	Japan

Note: Vinex™ is a copolymer of polyvinyl acetate with poly(alkyleneoxy) acrylate.

Applications

PVOH can generally be utilised in a range of film applications.

Degradation Mechanisms and Properties

The degradation of PVOH is influenced by its crystalinity and molecular weight. Testing carried out by Swinburne University have shown that PVOH does not biodegrade, but simply dissolves in water. Literature from PVOH manufacturers such as Kuraray Co. Ltd. indicated that PVOH can be biodegraded by activated sludge treatment. Biodegradation of PVOH in soil is expected be very slow.

4.1.2 Ethylene Vinyl Alcohol (EVOH)

EVOH is another water–soluble synthetic plastic, and is used as an oxygen barrier layer in multilayer film packaging. The high cost of EVOH is a significant barrier to its widespread use in other biodegradable plastics applications.

4.2 Photo-biodegradable Plastics

Photodegradable plastics are thermoplastic synthetic polymers into which have been incorporated light-sensitive chemical additives or copolymers for the purposes of weakening the bonds of the polymer in the presence of ultraviolet radiation. Photodegradable plastics are designed to become weak and brittle when exposed to sunlight for prolonged periods. Photosensitisers used include diketones, ferrocene derivatives (aminoalkyferrocene) and carbonyl-containing species. These plastics degrade in a two-stage process, with UV light initially breaking some bonds leaving more brittle lower molecular weight compounds that can further degrade from physical stresses such as wave action or scarification on rocks.

Developments

Photodegradable products can have a positive impact on plastic litter in both land and marine situations. The effectiveness is dependent on exposure intensity and will vary with factors such as the season, geography, dirt or water cover, and shading. A new approach to making photodegradable plastics involves adding catalytic metal salts or chelates to initiate the breakdown process.

Applications

Photodegradable plastics may be useful in applications where littering is an issue and in those that pose a threat to animal and marine life (i.e. six-pack plastic beverage rings).

Degradation Mechanisms and Properties

In photodegradable systems, biodegradation occurs only after an initial photo-degradation stage. Degradation of the polymer is triggered by UV light, and assisted by the presence of UV sensitisers in the polymer. The polymer is initially converted to low molecular weight material (i.e. waxes), and then converted to carbon dioxide and water by bacterial action.

4.3 Controlled Degradation Additive Masterbatches

Additives that impart controlled degradation behaviour to conventional thermoplastics, as well as to inherently biodegradable plastics, are becoming a popular strategy due to price competition. Such additives are known as prodegradant concentrates, and are generally based on catalytic transition metal compounds such as cobalt stearate or manganese stearate. The additive is typically used at levels of 1-3% and leads to additional costs of between 10-35% over that of polyethylene.

Developments

The principal company that has developed these prodegradant additives is EPI Environmental Technologies (Conroe, TX, USA) and their products are trademarked TDPA™ - an acronym for Totally Degradable Plastic Additives. Plastic products manufactured with EPI's TDPA technology progressively degrade to lower and lower molecular weights. They become brittle, disintegrate and are ultimately digested by microorganisms back to the basic elements of carbon dioxide (CO_2), water (H_2O) and biomass with no harmful residues. TDPAs have been shown not to affect bacteria, fungi or earthworms and they leave no hazardous residues. TDPAs can control the degradation rates of plastics in various degrees, from as short as a few weeks to months or years, at a competitive cost.

The prodegradants developed by EPI are also known as degradable and compostable polymer (DCP) additives. Compostable bags and bin liners that utilise polyethylene modified by DCP additives are claimed to totally degrade within 90 days in commercial composting facilities. Such prodegradant additives are also being marketed by CIBA under the trade name Envirocare™.

Prodegradant containing films represent a significant development over earlier biodegradable films based on starch-filled polyethylene. The starch-based bags had significantly inferior physical and mechanical properties compared with polyethylene; the prodegradant containing films on the other hand possess the same mechanical properties as polyethylene. A biodegradable additive marketed under the tradename Bioefect™ is used in polyolefins such as polypropylene.

In Australia a number of companies are using such pro-degradant additives. Enviro Covers Australia (Nerang, Qld) is distributing degradable polyethylene landfill covers based on the EPI technology. Valpak (Cromer, NSW) are producing degradable plastic bags called BioBag™ also based on the EPI technology.

AMCOR Flexibles have licensed this technology from EPI which allows them to produce plastic film and bags that will degrade in a dry landfill. The films are made by adding a prodegradant masterbatch to standard polyethylene. The additive, a metal chelate, initiates chain scission processes that cause the polymer chain to be reduced to molecular weights 20% that of the original, at which point bacterial degradation takes over. The additive is used at relatively low levels and contributes little add-on cost. The process begins essentially as soon as the film is extruded.

Such prodegradant containing films possess the same mechanical properties as polyethylene which represents a significant development over earlier starch-filled polyethylene films which had inferior physical and mechanical properties.

Applications

Potential applications include:

- Thin plastic shopping bags. Such bags would contain 1% of the pro-degradant additive and would take approximately 18 months to fully degrade in landfill.
- Daily landfill covers.
- Compostable bags and bin liners for food waste such as that from major catering events and commercial premises. Such bags would contain approximately 3% of the additive and would take 8-10 weeks to fully degrade.
- Plastic films used in fresh food wrapping and plastic wrap used in catering industries. The reason that a biodegradable film is advantageous in these areas is that a significant amount of food waste from catering companies and shopping centres can potentially go to commercial composting facilities. In such applications the current plastic wrap over vegetables for example, is a non-degradable contaminant in the compost.
- Agricultural mulch film where removal of the film after the growing season is expensive (30% that of the film cost).

Degradation Mechanisms and Properties

The addition of a ‘masterbatch’ (i.e. concentrate) to a plastic base resin allows for degradation behaviour to be controlled. Polyethylene containing 3% of the additive is claimed to degrade to a 95% weight loss after 4 weeks at 60°C. Such environmentally degradable plastic compositions are not strictly biodegradable but rather ‘bioerodable’.

DCP-containing polymers do not initially biodegrade, but rather chemically oxidise to lower and lower molecular weights, become brittle and fragment. The fragments are then ingested slowly by microorganisms, ultimately leaving carbon dioxide, water and biomass. As a consequence, DCP-containing plastics do not meet the ASTM D6400-99 standard, due to their degradation through chemical oxidation before the onset of biodegradation and because the mineralisation occurs at a slower rate than is acceptable.

Envirocare™ additives promote oxidative degradation of plastics such as standard polyethylene. Although the additives promote an oxidation process of the polymer, neither light nor heat is essential, and the additives can work at ambient temperature. When the molecular weight of the plastic drops sufficiently, the plastic is effectively converted to wax and at this point it will naturally biodegrade.

5 EMERGING APPLICATION AREAS IN AUSTRALIA

Until recently, the high cost associated with biodegradable plastics meant that they had limited penetration into the Australian markets of conventional commodity polymers. With the advent of new more affordable biodegradable plastics and prodegradant additives, it is predicted that by 2005 many biodegradable plastics will be cost competitive with conventional plastics, both in Europe and North America, over a broad range of applications (Kitch, 2001, p.74). Therefore, biodegradable plastics are potentially poised to expand their entry into the Australian market.

In general, biodegradable plastics are most suited to applications where the biodegradable plastic alternative has been shown through life cycle assessment (LCA) or other methods to achieve the following:

- Meets the overall needs of the application with additional technical and potential environmental benefits;
- Reduces labour or energy required to manage solids (e.g. composting facilities); and
- Reduces the environmental and social impact of other conventional products.

With the development of various biodegradable plastics with differing structures, properties and degradation behaviours, a range of potentially suitable application areas are emerging. For example, starch-based polymers may be suitable in agricultural and horticultural applications where no in-organic residues can result, and polymers with prodegradant additives, which maintain their structural integrity until they undergo composting, may be suitable for food waste bags.

Biodegradable plastics are well placed to substitute conventional plastics in low-weight, miscellaneous packaging applications that are not currently mechanically recycled. For example, certain streams of packaging such as take-away food containers, thermoformed biscuit trays and plastic food wrap are not collected and sorted for mechanical recycling at present and therefore may lend themselves well to substitution by biodegradable plastics that can be bioassimilated in compost. Furthermore, their high level of food residues enables such products to be compostable.

Some of these emerging application areas in Australia are outlined below.

5.1 Coated Paper

Coated (or laminated) paper products represent a significant market for biodegradable plastics. The present paper products for hamburger wrappers and disposal cups are extrusion-coated with low-density polyethylene film that is resistant to biodegradation. It also retards the biodegradation of the paper substrate since it acts as an impervious barrier.

5.2 Agricultural Mulch Film

Agricultural mulch films are utilised in some agricultural applications, such as tomato cropping, as a mulch soil cover to inhibit weed growth and retain soil moisture. These films could be potentially made from biodegradable plastics to eliminate the need for mechanical removal, as the mulch films could be ploughed into the soil. These films could also prevent the loss of topsoil humus that can be removed along with the waste film, and also enrich the soil with additional carbon.

A range of the biodegradable plastics available may be suitable for this application - such as TPS, AAC and controlled degradation masterbatches. Degradable starch-filled conventional polyethylene films may be unacceptable due to residuals that can build up in the soil over time (Kitch, 2001).

5.3 Shopping Bags

Plastic bags and other packaging films have a high profile in the Australian waste stream, as these materials are currently not widely accepted in the kerbside recycling system. Biodegradable plastics present a potential alternative to these materials in some applications.

5.4 Food Waste Film and Bags

Film, wrap and bags for food scraps, food residuals and food products destined for composting in commercial composting facilities, is a potential application area for biodegradable plastics. Conventional plastics are a significant contaminant in organics processing and they reduce the marketability of the compost produced (Goldstein & Block, 2000). These applications depend on the disposal environment being a commercial composting operation which provides the necessary conditions for the polymers to degrade.

An application for biodegradable plastics is for plastic films used in fresh food wrapping and plastic wrap used in catering industries. The reason that a biodegradable film could be advantageous in these areas is that a significant amount of food waste from catering companies and shopping centres can potentially be diverted to commercial composting facilities.

If composting of municipal solid waste and food waste becomes more prevalent, this may dramatically increase demand for biodegradable plastics in the form of compost bags and food scrap bags. For example, numerous towns in Northern Italy have been using biodegradable bags for transporting food residuals since 1998 (Kitch, 2001) and a major European producer of biodegradable plastics, Novomont, receives the majority of its revenue from compostable food bags and has a 10,000 tpa production plant servicing this market. Such bags would take 8-10 weeks to fully degrade in a commercial composting operation.

5.5 Consumer Packaging Materials

One of the major potential application areas for biodegradable plastics is consumer packaging. A wide range of plastic consumer packaging materials are not currently mechanically recycled, and may therefore be suited to the use of biodegradable plastics; however, life cycle assessment studies are needed to determine the impacts of biodegradable and conventional polymers for these uses. The various uses and likely disposal environments of different packaging products would require the use of different biodegradable plastics with appropriate mechanical and degradation properties.

Another strategic fit for biodegradable plastics is the beverage six-pack rings market. In the USA almost all plastic six-pack rings have been made of photodegradable LDPE plastic since the early 1990's. At least 16 US states—including Massachusetts, New York and Rhode Island - have passed laws requiring six-pack holders be biodegradable (these are marked by a small diamond between the rings). Pepsi for example, has a policy to purchase only photodegradable plastic six-pack rings. It should be noted that photodegradable plastics are not a complete solution in themselves as they require 6-8 weeks of sunlight to degrade and will not degrade if buried.

Other related applications include bread bags, bait bags, disposable food preparation gloves, drinking straws, and loose fill packaging.

5.6 Landfill Cover Film

The use of biodegradable plastic films as degradable daily landfill covers could considerably extend landfill life. Landfills require a daily cover, currently usually soil, to discourage flies and other disease carriers, control odour, minimise windblown litter and discourage scavenging birds and other animals. Using soil for the daily cover typically results in a 25% loss of available landfill space.

5.7 Other Applications

Other potential applications for the range of biodegradable plastics include:

- ❑ Bait bags;
- ❑ Fishing line and nets;
- ❑ Silage wrap;
- ❑ Body bags and coffin liners;
- ❑ Nappy backing sheet;
- ❑ Various sanitary product applications; and
- ❑ Cling wrap.

6 STANDARDS AND TEST METHODS

Australia at present has no standards, or test methods, that specifically apply to biodegradable plastics. There are however a range of international standards, and test methods, developed specifically for biodegradability, product safety, and also for compost derived products.

The main international organisations that have established standards or testing methods are:

- American Society for Testing and Materials (ASTM) (www.astm.org);
- European Standardisation Committee (CEN) (www.cenorm.be);
- International Standards Organisation (ISO) (www.iso.org);
- Institute for Standards Research (ISR),
- German Institute for Standardisation (DIN); and
- Organic Reclamation and Composting Association (ORCA) (Belgium).

These standards and testing methods are summarised below.

6.1 Biodegradation Standards and Tests

6.1.1 American Society for Testing and Materials

A family of ASTM standards addresses physical property deterioration in a variety of specific environmental conditions including simulated composting (D5509, D5512), simulated landfill (D5525), aerobic microbial activity (D5247) and marine floating conditions (D5437).

A second group of ASTM standards addresses CO_2 generation in aerobic environments including sewage sludge (D5209), activated sewage sludge (D5271), and controlled composting (D5338).

A third group of ASTM standards addresses CH_4/CO_2 evolution in anaerobic environments such as anaerobic sewage sludge (D5210), anaerobic biodegradation (D5511), and accelerated landfill (D5526). D6400 differentiates between biodegradable and degradable plastics, and D5152- addresses environmental fate.

The test methods for the key ASTM standards are summarised below,

ASTM D5338-93 (Composting)

For biodegradable plastic materials to be accepted in composting plants, both biodegradability and disintegration are important. Disintegration is the physical falling apart of the biodegradable plastic material, or more precisely of the product that has been made from it, into fine visually indistinguishable fragments at the end of a typical composting cycle.

A compostable material is understood to be a material in which:

- the polymer chains break down under the action of micro-organisms (bacteria, fungi, algae);
- total mineralisation is obtained (conversion into CO_2, H_2O, inorganic compounds and biomass under aerobic conditions); and
- the mineralisation rate is high and is compatible with the composting process.

Those materials having a degree of biodegradation equivalent to that of cellulose (maximum permissible tolerance of 5%) are considered to meet the compostability criteria under these standards.

To measure compostability, the ASTM in the United States has developed the key standard ASTM D5338-93. This is a standard test method for determining aerobic biodegradation of plastic materials under controlled composting conditions. In this method the plastic is mixed with stabilised and mature compost derived from the organic fraction of municipal solid waste. The net production of CO_2 is recorded relative to a control containing only mature compost. After determining the carbon content of the test substance, the percentage biodegradation can be calculated as the percentage of solid carbon of the test substance which has been converted to gaseous carbon in the form of CO_2. In addition to carbon conversion, disintegration and weight loss can be evaluated.

To meet the ASTM D5338-93 standard, 60% of single polymer materials must mineralise in six months, and 90% must do so in blends. Materials should give way to intense microbial activity and be converted from carbon to carbon dioxide, biomass and water. Materials also should begin to fragment, at which point disintegration begins. In this phase, the material must completely physically and visually disintegrate. Ninety percent of the disintegrated material must not adversely affect the quality of the compost. Finally, even after land application, remaining materials should be safely converted into carbon dioxide by microorganisms. The resultant compost should not be toxic and should not deter plant growth.

ISO CD 14855 and the CEN test procedures are similar to the ASTM D 5338-92. The only difference is the temperature profile which is continuously at 58°C in both ISO and CEN procedures while it follows a temperature profile of 35-58-50-35°C in the ASTM test.

ASTM D5209-91 (Aerobic, Sewer Sludge)

The Sturm test (ASTM D5209-91) was developed to measure the biodegradability of both water-soluble and insoluble compounds in an aquatic environment. As with ASTM D5338-93 these tests are based on the measurement of CO_2 produced during biodegradation of the plastic test material. The percentage biodegradation is calculated from the CO_2 produced by the plastic sample compared to the total theoretical amount. Continuous aeration ensures that there is sufficient oxygen in the bioreactor at all times. The measurement of carbon dioxide evolved during degradation gives direct information on the bioconversion of the carbon backbone of the polymer to metabolic end products.

A 10 mg plastic sample is used in the test. For this reason it gives an artificially high breakdown rate. While the measurement of evolved CO_2 is very accurate the rate of biodegradation can have an error of up to 80%.

The Technical Research Centre of Finland (VTT) have developed a 'headspace test', which like the Sturm test, is also based on the measurement of carbon dioxide under aerobic conditions. The VTT test is performed in 'headspace' bottles (volume 125 mL) containing 50 mL of a mineral nutrient medium and sewage sludge. The benefits of the VTT test are its simplicity and the ability to conduct an extensive number of samples simultaneously and thereby perform statistical evaluation. The carbon dioxide evolved during biodegradation is determined from the gas and liquid phases at weekly intervals.

ASTM D5210-92 (Anaerobic, Sewage Sludge)

Anaerobic degradation is biodegradation in the absence of oxygen. A mixed population of microorganisms is needed for complete degradation of the polymer. In the first stage, acidogenic bacteria convert organic substances into lower molecular weight components such as alcohols and short chain fatty acids. Subsequently acetogenic bacteria further degrade these substances to acetone, carbon dioxide and hydrogen. In the final phase, methane and carbon dioxide are the end products of anaerobic degradation.

The standard test method for determining the anaerobic degradation of plastic materials is ASTM D5210-92. This test measures the amount of biogas released during polymer biodigestion by microorganisms. The biodegradation percentage is the ratio of biogas produced by the test sample compared with the theoretical amount produced in the case of complete mineralisation.

ASTM D5511-94 (High-solids Anaerobic Digestion)

ASTM D5511-94 is the standard test method for determining anaerobic biodegradation of plastic materials under high-solids anaerobic digestion conditions. This method determines the inherent biodegradability of plastic in an anaerobic solid waste digester or a sanitary landfill under optimal conditions. In this case the total volume of biogas produced per unit weight of sample is measured. Knowing the carbon content of the test material, the percentage of biodegradation can be calculated as the percentage of solid carbon in the sample which has been converted to gaseous carbon in the form of CH_4 and CO_2.

ASTM Tests for Specific Disposal Environments

Tests to evaluate the generation and quality of humic substances in landfills, composting or terrestrial or aquatic environments are beginning to appear. Aerobic composting with activated vermiculite provides the opportunity to recover and quantify the polymeric residues, allowing more complete carbon balances as well as assessments of toxic compound generation and humus quality.

The property of disintegration of biodegradable plastics can be measured in a pilot-scale or full-scale composting test. The test substance is subjected to a spontaneous composting process for a duration of 12 weeks. At the end, a sieving over 2 mm followed by a precise sorting analysis is executed. It may be that a bioplastic passes the test at a specific thickness but fails the test at a higher thickness. It must also be demonstrated that the bioplastic materials have no negative effect on compost quality. This involves chemical analyses (e.g. heavy metals), required to evaluate conventional compost quality. In addition, ecotoxicity tests are advised, including plant germination tests as well as animal toxicity tests. The purpose of these tests is to make sure that small additives (e.g. from the plastics) do not have an adverse effect on compost quality.

6.1.2 International Standards Research

The performance of biodegradable plastics in composting facilities and under laboratory conditions has been studied by International Standards Research (ISR). ISR has determined that plastics need to meet the following three criteria in order to be compostable:

- They must biodegrade at the same rate and to the same extent as known compostable material such as garden waste and paper, and leave no persistent or toxic residues.
- They must disintegrate during active composting so there are no visible or distinguishable fragments found on the screens.
- They must have no ecotoxicity or phytotoxicity that may impact on the ability of the compost to support plant growth.

6.1.3 International Standards Organisation

Three International Standards Organisation (ISO) standards have set the criteria by which European biodegradable plastics are currently assessed. These are:

- ISO 14855 (aerobic biodegradation under controlled conditions);
- ISO 14852 (aerobic biodegradation in aqueous environments); and
- ISO 15985 (anaerobic biodegradation in a high solids sewerage environment).

ISO 14855 is a controlled aerobic composting test, and ISO 14851 and ISO 14852 are biodegradability tests specifically designed for polymeric materials.

An important part of assessing biodegradable plastics is testing for disintegration in the form in which it will be ultimately used. Either a controlled pilot-scale test or a test in a full-scale aerobic composting treatment facility can be used. Due to the nature and conditions of such disintegration tests, the tests cannot differentiate between biodegradation and abiotic disintegration, but instead demonstrates that sufficient disintegration of the test materials has been achieved within the specified testing time.

6.1.4 European Committee for Normalisation

The European Committee for Normalisation (CEN) established the norm standard (CEN prEN 13432) in 1999. The norm provides the European Commission's *European Directive on Packaging and Packaging Waste* with appropriate technical regulations and standards. This norm is a reference point for all European producers, authorities, facility managers and consumers.

The standard specifies requirements and procedures to determine the compostability of plastic packaging materials based on four main areas:

- biodegradability;
- disintegration during biological treatment;
- effect on the biological treatment process; and
- effect on the quality of the resulting compost.

Importantly, the packaging material that is intended for entering the bio-waste stream must be 'recognisable' as biodegradable or compostable, by the end user.

The strictest European standard for biodegradability is CEN 13432. This standard can apply to other packaging materials in addition to polymers, and incorporates the following tests and standards:

- ISO 14855;
- ISO 14855 (respirometric);
- ISO 14852;
- ASTM D5338-92;
- ASTM D5511-94;
- ASTM D5152-92;
- ASTM E1440-91;
- Modified OECD 207; and
- CEN TC 261/SC4/WG2.

For a material to pass the standard, it must not persist for longer than 6 months under any of the conditions stipulated in the above tests and have a pass level of 90%. In addition, the material must not exceed a heavy metals content above 50% of that for 'normal' compost, as follows:

Zn 150 ppm
Cr 50 ppm
Cu 50 ppm
Mo 1 ppm
Ni 25 ppm
Se 0.75 ppm
Cd 0.5 ppm
As 5 ppm
Pb 50 ppm
F 100 ppm
Hg 0.5 ppm

'OK Compost' Certification and Logo

The 'OK Compost' logo can be used on the labelling of biodegradable plastics and other materials to signify that the material is 100% compostable and biodegradable. The logo is owned and managed by AVI, and is based on the CEN – 13432 standard.

6.2 Compost Toxicity Tests

For a comprehensive assessment of toxicity associated with compost applications, plastics can be tested on both plant and animal species.

Toxicity screening of some commercial degradable plastics using cell culture testing has been reported by Dang et al. (1997). A number of polyester types were tested including a plasticized cellulose acetate, an aliphatic polyester (Bionolle), polyhydroxybutyrate-co-hydroxyvalerate (Biopol™), and polycaprolactone (TONE™ polymer). Cell culture medium with serum was used as the extraction medium. The relative MTT activity of cells cultured in fresh extracts indicate that TONE™ polymer (all shapes) and Bionolle (test bars and films) are comparable to materials currently used in food with no toxic effects on cells (Dang et. al; 1997).

Plant Phytotoxicity Testing

While a product may not negatively impact plant growth in the short term, over time it could become phytotoxic due to the build-up of inorganic materials, which could potentially lead to a reduction in soil productivity. For this reason some manufacturers use plant phytotoxicity testing on the finished compost that contains degraded polymers.

Phytotoxicity testing can be conducted on two classes of flowering plants. These are monocots (plants with one seed leaf) and dicots (plants with two seed leafs). Representatives from both of these classes are typically used in toxicity testing - summer barley to represent monocots and cress to represent dicots. Tests involve measuring the yield of both of these plants obtained from the test compost and from control compost.

Animal Toxicity Test

Animal testing is generally carried out using earthworms (as representative soil dwelling organisms) and Daphnia (as representative aquatic organisms). Earthworms are very sensitive to toxicants. Since earthworms feeds on soil, they are suitable for testing the toxicity of compost.

In the acute toxicity test, earthworms are exposed to high concentrations of the test material for short periods of time. The toxicity test is a European test (OECD guideline #207) in which earthworms are exposed to soil and compost in varying amounts. Following 14 days of exposure, the number of surviving earthworms is counted and weighed and the percent survival rate is calculated. The earthworms are exposed to several mixture ratios of compost and soil mixtures.

Compost worms (Eisenia fetida) are used for testing the toxicity of biodegradable plastic residues. These worms are very sensitive to metals such as tin, zinc, heavy metals and high acidity. For this test worms are cleaned and accurately weighed at intervals over 28 days. The compost worm toxicity test is considered to be an accurate method.

The Daphnia toxicity test can establish whether degradation products present in liquids pose any problem to surface water bodies. In the test, Daphnia are placed in test solutions for 24 hours. After exposure the number of surviving organisms is counted and the percent mortality is calculated.

6.3 Difference Between Standards for Biodegradation

The main point of differentiation between the various international standards is the percentage of biodegradation required for compliance. This is an important issue that is under discussion at ISO level. The compliance requirements for the key standards are shown in Table 6.1.

Table 6.1 – Standards Compliance Requirements

Standard	Biodegradation Requirement	
DIN	60%	6 months
ASTM	60%	6 months
CEN	90%	Nil
OECD	60% (for chemicals)	28 days

A 60% biodegradation of a chemical (that is, small molecules) will generally represent a strong modification of its original chemical structure. On the other hand, if a copolymer is formed by two monomers statistically distributed, say 60% A and 40% B, where A is biodegradable and B is recalcitrant, a 60% biodegradation may mean a 100% biodegradation of one component but a 0% biodegradation of the other.

6.4 Development of Australian Standards

There is a need for the adoption of Australian Standards for biodegradation which match the potential application areas and disposal environments in Australia. These Standards may be developed with reference to the existing international standards.

A number of products presently being imported into Australia are purported to be biodegradable plastics, but are simply hydrocarbon polymers such as polyethylene. It is currently difficult to verify whether polymers comply with relevant overseas standards other than by conducting expensive testing. For example, the knives and forks from the Sydney Olympics have been tested in laboratory compost vessels and were found not to breakdown after 6 months. The development of Australian Standards that address local requirements and circumstances may alleviate these problems.

7 DISPOSAL ENVIRONMENTS

The rate of biodegradation of biodegradable plastics is dependent on the disposal environment and its conditions.

The major disposal environments for biodegradable plastics are:

- ❑ composting facilities or soil burial;
- ❑ anaerobic digestion;
- ❑ wastewater treatment facilities;
- ❑ plastics reprocessing facilities;
- ❑ landfill;
- ❑ marine and freshwater environments; and
- ❑ general open environment as litter.

To a large extent, the nature of the biodegradable plastic application should dictate the disposal environment.

7.1 Composting Facilities and Soil Burial

Most biodegradable plastics lend themselves well to composting systems. Composting and soil burial is the preferred disposal environment for most biodegradable plastics. Many cities around the world now compost garden organics, food wastes, cardboard, paper products, mixed municipal solid waste and sewage sludge.

The degradation mechanism of biodegradable plastics in a composting environment is primarily hydrolysis combined with aerobic and anaerobic microbial activity. Composting technologies range from windrowing to in-vessel and trench composting.

In composting, material is turned or an air blower distributes air under the pile to maintain aerobic conditions for faster degradation, redistribute material and moisture and to maintain porosity of the compost. The mechanical stress imposed by turning the compost piles often facilitates the initial physical disintegration of plastic items to a primary dimension of about one-inch. Typically for full degradation, composting occurs over a 10 to 12 week period. The degradation products of aerobic composting are compost and $CO_{2.}$

The following pre-treatment steps are required before beginning the composting process:

- ❑ Removal of bulky non-compostable items;
- ❑ Particle size reduction;
- ❑ Moisture addition; and
- ❑ Mixing.

Compost increases soil organic content. Humus results from the degradation of lignin, carbohydrate and proteins, and is also formed when many biodegradable plastics degrade. Humus is beneficial to the soil as:

- the dark colour improves springtime warming of the soil;
- the physical structure keeps the soil light and fluffy, which improves air penetration into the soil and root growth;
- the physical structure increases soil moisture retention; and
- the complex chemistry creates a colloidal system that controls pH, retains necessary minerals such as Ca, Mg, and K, and traps heavy metal toxins to limit availability to the plants.

Key Factors Defining Compostability

The four main factors which are generally considered as fundamental in order to define the compostability are outlined below.

(1) Physical Persistence

The physical persistence of a plastic material in compost derived product is unacceptable. The initial plastic material must not be physically recognisable in the final compost. The total disappearance of a plastic material can be achieved by disintegration, dissolving or melting.

(2) Chemical Persistence

In nature, organic materials are recycled through mineralisation, a process by which the carbon atoms of organic materials are incorporated into the microbial biomass and then, under aerobic conditions, oxidised to CO_2. Compostable synthetic materials are expected to behave in the same manner. Their biodegradability is necessary to avoid accumulation of man-made materials in the soil. If this were not the case, composting would simply be the process of transformation of ‘visible’ solid waste into ‘invisible’ waste by its dissemination into the soil.

(3) Toxicity

Synthetic polymeric materials should not release toxic compounds into the final compost in order to prevent negative effects on the environment, organisms and humans via the food-chain. This issue is strictly linked to chemical persistence.

(4) Effect on Quality of Compost

The addition of biodegradable plastics to composting processes must not affect the quality of the final compost product. The assessment for the quality of compost should not be confused with toxicity (i.e. a compost can be a good plant fertiliser and yet be contaminated with toxic molecules).

7.2 Anaerobic Digestion

Anaerobic digestion, using thermophilic microbes to produce methane and compost, is also gaining support as an alternative to landfills. Methane production may be faster, more efficient and more predictable in this system and a useful end-product, compost, is also produced.

7.3 Waste Water Treatment Plants

Sewage is an excellent environment for biodegradation of biodegradable plastics as there is a preponderance of microbes and high levels of nitrogen and phosphorous. Activated sewage sludge will convert approximately 60% of a biodegradable polymer to carbon dioxide while the remaining 40% will enter the sludge stream where, under anaerobic digestion, it will be converted to methane.

Any biodegradable polymer that meets the compostability criteria will degrade even faster in a sewage environment. A rapidly degradable (or soluble) polymer that will not restrict sewer systems is needed if it is to be disposed through wastewater treatment plants.

Biodegradable plastics have the potential to be used in various flushable sanitary product applications such as sanitary towels, colostomy bags and other absorbent products. In addition, effluent from recycling activities must be treated in wastewater treatment plants and may contain biodegradable plastics.

Flushable biodegradable plastics can have an adverse impact on wastewater treatment plants due to the very fast throughputs, typically 4 to 8 hours, from the drain to the plant. This length of time is insufficient for many biodegradable plastics to lose their structure. Such plastics can foul the wastewater treatment plant primary screens. Ill conceived biodegradable plastics would only contribute to this problem. Flushable biodegradable plastics can be evaluated in a laboratory using activated sludge as the test medium.

7.4 Reprocessing Facilities

It is to be expected that if biodegradable plastics began to occupy a significant market share of the plastics market in Australia that some material would end up in plastics reprocessing facilities. This could have significant effects on the sorting procedures required and the quality of recycled end products. These issues are covered in more detail in Section 9.

7.5 Landfills

A recent study by Japanese researchers found that when conventional low-density polyethylene film was under bioactive soil for almost 40 years, the surface of the film showed signs of biodegradation with the molecular weight dropping by half the original. The inner part of the sample was almost unchanged with the molecular weight being retained (Ohtake, 1998).

Although the majority of biodegradable plastics are more easily degraded in composting and soil disposal environments than conventional plastics, environmentally degradable polymers could increase the capacity of landfill sites by breaking down in a relatively short time and freeing other materials for degradation, such as food scraps in plastic bags. Biodegradable plastics will not degrade appreciably in a dry landfill, however, unless they contain sensitisers and pro-oxidants (Garcia et al, 1998), which are transition metal catalysts such as manganese stearate or cobalt stearate.

Biodegradable plastics also make a contribution to landfill gas production, and in landfills where gas is collected for use as an alternative energy source this can be a positive outcome. Conversely however, where gas utilisation systems are not in place, the presence of biodegradable plastics will increase greenhouse gas emissions. Anaerobic microbes in the presence of water in the landfill will consume natural products and produce methane, CO_2, and humus. Typical landfill gas contains 50% methane and 45% CO_2, with the balance composed of water and trace compounds. To compliment landfill gas production, degradable polymers need to be consumed by anaerobic microbes to produce methane at rates comparable to those generated by degradation of natural products (i.e. lignin and cellulose in paper and garden waste).

Biodegradable plastic films can also be used for degradable landfill covers (see Section 6.6).

7.6 Marine and Freshwater Environments

The rate of biodegradation in marine environments is affected by the water temperature. In cold waters, the plastic material may still be in a form that could endanger marine life for an extended period of time. In some initial trials carried out by Plastral Fidene, a starch-PCL blend was found to degrade in 20 weeks in Queensland waters and 30 weeks in South Australian waters;. the same sample was found to fully degrade in 20-30 days in a compost environment (pers. comm. W. Hall, Plastral Fidene, 2002). Thus seasonal and climatic effects on biodegradation rates need to be considered in relevant applications.

As biodegradable plastics have degradation behaviours based on particular environmental conditions, many biodegradable plastics may not degrade rapidly in the intestines of marine species, and injury is likely to remain an outcome (see Section 10.1). No studies have been done to date on the rate of degradation of biodegradable plastics in the gut of marine species and indeed ethics approvals for such work would be very difficult to obtain.

7.7 Litter

Plastic litter causes aesthetic problems as well as trauma to wildlife resulting from entanglement and ingestion of plastic packaging materials and lightweight bags. Wildlife losses are an issue for the conservation of biodiversity, and losses due to litter have caused public concern.

Biodegradable plastics should not be regarded as a panacea to the visible plastic litter problem. The breakdown of biodegradable plastics is not instantaneous, and at the least requires the presence of microbes in order to biodegrade. For instance, shopping bags hanging from branches above the waterline of streams and rivers is a much publicised form of plastic litter. The visual impact of this will not be lessened by biodegradable shopping bags since plastic in such environments is not exposed to microbes and may take more than a year to begin to decompose. Where photodegradable plastics are utilised, similar problems can occur where the conditions required for full degradation are not met.

8 PLASTICS SORTING AND REPROCESSING

The plastics recycling collection, sorting and reprocessing industry is well established in Australia, from pre-consumer industrial scrap right through to post-consumer domestic packaging materials. This situation has led to the development of a viable plastics reprocessing industry in Australia, and a high level of plastics waste export to Asian reprocessing markets. The National Plastics Recycling Survey undertaken by Nolan-ITU for PACIA (2002) showed a total of 164 000 tonnes of plastics recycled in 2001.

Most plastics are sorted and reprocessed as specific polymer types. Over the past decade, a polymer identification code has been added to many products to assist consumers and reprocessors to identify which plastics can be recycled. Advice to consumers on the scope of recycling is often a combination of reference to the polymer identification code and the product or packaging application (eg. beverage bottles marked with a 1, 2 or 3).

8.1 Key Issues

The plastics reprocessing industry and policy makers are concerned about the potential impact of biodegradable plastics on the current mechanical recycling industry and its continued expansion. One of the challenges faced by the plastics recycling sector over the past decade has been to build confidence in the technical integrity of the reprocessed material and to demonstrate its ability to perform as a viable alternative to virgin plastics.

Of greatest concern is the possibility that a proportion of reprocessed plastic will contain biodegradable material. This could result in changing the characteristics of the material (flow rates, strength etc). Most importantly it may lead to a failure of products as degradation occurs. Even a minor increase in failure would be significant in applications such as pipe fittings or liquid packaging. The growing confidence in recycled plastics will be eroded if this technical integrity is comprised.

8.2 Recyclable Plastics Sorting Considerations

Plastic sorting and separation is required to produce quality end products and maximise economic return. Most plastics are mutually incompatible with each other. If incompatible plastics are melt blended (by extrusion) then on cooling the mixture phase separates and the resultant products usually have low mechanical properties since cracks develop through the plane of weakness between the immiscible phases. Plastic enrichment and purification to a level to enable marketability of the recyclate is therefore necessary.

A range of measures are used to sort different plastics. Manual sorting is the most basic form of separating plastic categories. This is then backed up at some plastics reprocessors with sorting technologies based on specific gravity or optical sorting equipment.

Perhaps the best current technologies to sort biodegradable plastics from non-biodegradable plastics is near infra-red (NIR) detection. In recent years a number of such systems have been commercialised including one wholly developed in Australia by Rofin Pty. Ltd. The basis of this plastics sorting system is the use of a near infra-red light beam that impinges on the plastic whilst it is moving rapidly (2 m/s) on a conveyor belt. The reflected light beam is collected and sent to a detector which can then positively identify the plastic type. An air jet then deflects the plastic article into a collection bin. This sorting technology is usually used for positive sorting - that is the plastics of interest are positively removed from the mixed stream and the unwanted plastic types remain on the conveyor and fall off the line into a waste bin that is generally landfilled.

NIR sorting systems are almost all used for rigid plastic packaging (bottles, jars trays, etc.). Since biodegradable plastics have a characteristically different NIR signature to commodity polymers such as PE, PET, PP they will not cross-contaminate the recycling processes for these polymers. In addition, the NIR system can be tuned, for example to positively sort starch-based polymers and in this way a pure biodegradable stream could be segregated for composting. Where cross-contamination is more likely, is in plastic film recycling. Presently plastic film is being collected and recycled (such as commercial pallet wrap, stretch and shrink wrap). Due to the nature of film it does not lend itself well to automated sorting techniques.

8.3 Reprocessing Considerations

Almost all biodegradable plastics are based on polar polymers such as polyesters, polyketones and polyalcohols. In each case, oxygen-containing functional groups are present in the polymer to provide sites for microbial attack. Common conventional packaging plastics on the other hand, such as polyethylene, polypropylene and polystyrene, are non-polar and are thus not compatible with biodegradable plastics.

Another consequence of the polar nature of biodegradable plastics is that they absorb moisture from the atmosphere and can have equilibrium water contents as high as 6% by weight. In thermoplastic starch biodegradable plastics, water is often deliberately added as a plasticiser to induce flexibility. During reprocessing in an extruder, recycled biodegradable plastics will liberate this water as steam and this will cause problems such as bubbles, blisters and broken strands during pelletisation and downstream fabrication. A key issue for consideration in this context is the likely variance in the quantities of biodegradable plastics within the recyclate, which would decrease the ability to produce an end product with consistent characteristics and quality.

Polyolefin Reprocessing

The likelihood of cross-contamination of polyolefins such as polyethylene and polypropylene by biodegradable plastics is high, given the fact that biodegradable plastics for film and flexible packaging applications have been designed to match, as far as possible, the appearance and characteristics of these polymers.

During recycling and extrusion of polyolefins both starch and PCL-based biodegradable plastics will tend to degrade and caramelise causing discoloration of the resultant recyclate. This is due to the limited thermal stability of biodegradable plastics - for example PCL begins to degrade at just 200°C. Starch materials begin to caramelise at slightly higher temperatures.

Given that polyethylenes and polypropylenes are reprocessed at temperatures of 220 - 240°C respectively, it is clear that melt degradation of biodegradable plastics is an issue. This is exacerbated by the fact that biodegradable plastics usually contain no thermal stabilisers or antioxidants.

Polyethylene Reprocessing

Biodegradable plastics containing prodegradant additives (such as the EPI films) could have a major impact on existing plastic recycling operations. Since the prodegradant-containing plastics are indistinguishable from conventional polyethylene they will almost certainly enter the polyolefin recycling stream. The prodegradant catalysts are so effective at sensitising polyolefins towards oxidative degradation that even low levels of such cross-contamination has the potential to destabilise large volumes of polyethylene recyclate.

Polyethylene recyclate is commonly used in strength critical applications such as builders film, dam liners, garbage bags, etc. In this way biodegradable plastic contamination in the conventional plastic recycling stream can undermine the integrity and mechanical properties of polyethylene recyclate. Since there is a time delay before the onset of accelerated degradation and concomitant loss of mechanical properties, failures would most probably be detected not during fabrication, but rather in the field where the loss potential and consequential damage would be highest.

9 POTENTIAL POSITIVE ENVIRONMENTAL IMPACTS

Full life-cycle assessment studies of biodegradable plastics in comparison to conventional petroleum-based plastics are required. However, environmental benefits that may be derived from the use of biodegradable plastics compared to conventional materials are outlined below.

9.1 Composting

Compost derived from biodegradable plastics along with other organic products increase soil organic carbon, water and nutrient retention, while reducing fertiliser inputs and suppressing plant disease. The composting of biodegradable plastics also cycles matter rather than 'locking' it up in persistent materials, particularly when the non-degradable plastics are destined for landfill.

9.2 Landfill Degradation

The use of biodegradable shopping and waste bags may have the potential to increase the rate of food degradation in landfills, and therefore have the potential to enhance methane harvesting potential where infrastructure is in place and decrease landfill space usage. The use of biodegradable plastic film as daily landfill covers has the potential to considerably extend landfill life, as they could replace traditional soil cover material which use approximately 25% of landfill space.

9.3 Energy Use

The energy required to synthesise and manufacture biodegradable plastics is shown in Table 9.1, along with values for high density and low density polyethylene. PHA biopolymers presently consume similar energy inputs to polyethylenes. New feedstocks for PHA (see Section 3.1) should lower the energy required for their production.

Table 9.1: Energy for Production of Biodegradable Plastics

Polymer	Energy (MJ/kg)
LDPE	*81*
PHA – fermentation process	81
HDPE	*80*
PCL	77
PVOH	58
PLA	57
TPS + 60% PCL	52
TPS + 52.5% PCL	48
TPS	25
TPS + 15% PVOH	25

Source: 'Review of Life Cycle Assessments for Bioplastics' by Dr. Martin Patel, Utrecht University, Netherlands, Nov. 2001.

9.4 Greenhouse Gas Emissions

An important environmental impact of biodegradable plastics is their contribution to greenhouse gas (GHG) generation when they biodegrade.

In the manufacture of hydrocarbon polymers, carbon is taken from one carbon sink (e.g. an oil deposit) to another carbon sink (plastic) with no net production of atmospheric carbon other than that generated during energy production for the conversion process.

Carbon in the form of carbon dioxide is 'fixed' during the growth of the plants, and can be used in the production of some biodegradable polymers. This carbon is then returned to the air when the polymers degrade. The EPI polymers on the other hand, convert carbon from petroleum deposits ultimately into atmospheric carbon. In this case, they are removing carbon from a carbon sink and contributing to greenhouse gases. Greenhouse gas emissions include manufacturing emissions as well as emissions from end-of-life waste treatment of biodegradable plastics are shown in Table 9.2.

Table 9.2: Greenhouse Gas Emissions from Biodegradable Plastics

Polymer	**GHG Emission x 10[kgCO2eq./kg]**
PCL	53
LDPE	*50*
HDPE	*49*
PVOH	42
TPS + 60% PCL	36
TPS + 52.5% PCL	33
TPS + 15% PVOH	17
Mater-Bi™ film grade	12
Thermoplastic Starch (TPS)	11
Mater-Bi™ foam grade	9
PLA	NA
PHA – ferment	NA

Source: ‘Review of Life Cycle Assessments for Bioplastics’ by Dr. Martin Patel, Department of Science, Technology and Society, Utrecht University, Netherlands, Nov. 2001.

As shown in Table 9.2, biodegradable plastics result in relatively low greenhouse gas emissions in comparison to some polyethylenes. This is particularly obvious for starch-based plastics.

10 POTENTIAL NEGATIVE ENVIRONMENTAL IMPACTS

10.1 Pollution of Aquatic Environments

Increased Aquatic BOD

Pollution from high nutrient levels in waterways, determined by high biological oxygen demand (BOD) and chemical oxygen demand (COD), lead to the degradation of aquatic ecosystems and algal blooms. The breakdown of starch-based biodegradable plastic materials can result in increased BOD if the plastics make their way into water ways.

Water Transportable Degradation Products

Plastic degradation by-products, such as dyes, plasticisers or catalyst residues, in landfills or compost can potentially migrate to groundwater and surface water bodies via run-off and leachate. Organisms inhabiting these water bodies could thereby be exposed to degradation products, some of which may be toxic.

Groundwater contamination from pigments, catalyst residues and isocyanate coupling agents may also occur. Liberated plastic additives and polymer degradation products in landfills or compost heaps can potentially migrate to nearby bodies of water through liquids percolating in the ground (leaching) or via rainfall run-off. If current metal-based pigments continue to be used in biodegradable plastics, then the potential for release and accumulation in soil and water is high.

Risk to Marine Species

Plastic pollution in marine environments can result in the death of marine species who ingest it in the belief that it is a jellyfish, squid or other translucent, amorphous organism. In the animals gut, biodegradable plastics will not degrade rapidly and injury to the animal is likely to remain an outcome. Turtles can die of starvation as plastic bags block the alimentary canal.

10.2 Litter

The visual impact of littering is unlikely to decrease with the use of biodegradable plastics since windblown plastic litter and plastic films/bags snagged on branches and bushes will not be exposed to sufficient level of microbes for proper biodegradation to take place. Consequently biodegradation of such litter may take many years. This problem may potentially be combined with the possibility that conspicuous littering by plastic may actually increase due to the belief by consumers that biodegradable plastics will disappear quickly in the environment.

10.3 Compost Toxicity

Composted biodegradable plastics will expose plants, soil dwelling organisms (such as worms) and aquatic organisms to polymer degradation products such as manufacturing residues or additives used in their formulation. Due to the complex nature of polymer breakdown, it is not possible to identify all the compounds present in a mix of degradation products, some of which may be toxic. Hence, the possible toxicity of biopolymer degradation products is assessed using toxicity tests (see Section 6.2).

10.4 Recalcitrant Residues

There is currently little evidence to show that recalcitrant polymer residues in the soil are harmful. Some results suggest that pure polymeric fragments may function like the long-lived components in humus and may provide useful properties as a soil additive.

Grass growing studies using municipal waste derived compost in combination with chopped plastic fibres demonstrated improved growing rate and root structure development to accelerate sod production (Gallagher, 2001). German studies indicate that crushed polystyrene foam improves the aeration of soil (Styropor Technical Information Bulletin, 1994), and is widely used in German orchards, vineyards and potting mixes as a soil conditioner.

However, fragments from partially biodegraded plastics will accumulate in cultivated soils and fragments such as polyethylene (which has a specific gravity less than one) could float and potentially block drains.

Further work is required to understand the fate and consequence of recalcitrant residues in the environment.

Aromatic Compounds

While the aliphatic portion of AAC polymers are biodegradable, the aromatic segments will form small molecules such as terephthalic acid (TPA) whose biodegradation is less certain. In other cases the residual compounds will be bishydroxyethylene terephthalate (BHET). Some new AAC are being made from bishydroxyethylene terephthalate (BHET), capralactone (CL) and tetra-n-butyl titanate ($Ti(OBu)_4$ as a catalyst. Accordingly their breakdown can result in the production of BHET which is the aromatic segment. Both TPA and BHET are also formed from the glycolysis of PET - the difference being PET does not undergo glycolysis or hydrolysis in the natural environment at appreciable rates.

10.5 Additives and Modifiers

Biodegradable polymers are rarely used on their own to make biodegradable plastics. A range of additives and modifiers (e.g. coupling agents, plasticisers, fillers, catalysts, dyes and pigments) are generally added to obtain useful performance properties that approach those of conventional plastics. Once the biodegradable polymer matrix degrades, the additives and modifiers become liberated into the environment. These compounds and their potential negative impacts are outlined below.

Isocyanate Coupling Agents

Starch and PLA do not have readily reactive functional groups, so their mutual compatibility is poor. To overcome this shortcoming a chemical with isocyanate functional groups such as methylene-diisocyanate, (MDI) is reactively blended with the starch and PLA. MDI is recognised as a toxic substance, however further studies are required to assess the problems that could occur if MDI entered the environment.

Plasticisers

Plasticisers are often added to increase biodegradable plastic flexibility. Typical plasticisers used in biodegradable plastics include:

- Glycerol;
- Sorbitol;
- Propylene glycol;
- Ethylene glycol;
- Polyethylene glycol;
- Triethyl citrate; and
- Triacetine.

Most of these are organic and readily fully break down in the environment.

Ethylene glycol, however, is a recognised environmental pollutant. Direct exposure to the compound can cause skin and eye damage in humans, with a lethal dose if ingested of 100mL. The lethal concentration for fish has been found to be 100mg/L. (Material Safety Data Sheet – Ethelyne Glycol, 2001).

Fillers

Fillers are often added to biodegradable plastics to reduce cost. Since fillers are generally inorganic, they have the potential to accumulate over time in soil or other disposal environments. Fillers are, however, often inert and of mineral origin, thus posing no toxicity concerns at the levels found in biodegradable plastics (Hohenberger, 2000, p.901). Typical fillers include:

- calcium carbonate (most common);
- titanium dioxide;
- talc; and
- silicon dioxide.

Catalyst Residues

Monomers are generally polymerised in the presence of certain catalytic metals in order to achieve sufficient commercial productivity. Remnants of the catalysts remain in the final polymers. In non-biodegradable plastics these catalyst residues remain encapsulated with the polymer matrix and are not mobile or leachable. In biodegradable plastics these catalyst residues are liberated and can enter the disposal environment. Table 10.1 shows the typical catalytic metals present in biodegradable plastics.

Table 10.1: Typical Metals in Biodegradable Plastics

Metal type	Polymer type
Tin	PLA, PCL
Antimony	Modified PET
Cobalt	Modified PET
Chromium	PE-blends
Cobalt Manganese	Prodegradant Polyethylenes
Titanium	Copolyesters

10.6 Prodegradants and Other Additives

Biodegradable plastics based on conventional thermoplastics that contain prodegradant additives (refer to Section 4.3) may cause negative environmental impacts because they:

- are not based on renewable resources;
- have the potential to disperse catalytic metals in to the environment;
- convert carbon from a carbon sink (oil) to atmospheric carbon and thus contribute to net greenhouse gas inventories; and
- disintegrate into tiny particles and do not truly biodegrade and the small fragments that remain still have too high a molecular weight to break down to low molecular weight materials.

10.7 Source of Raw Materials

The source materials for biodegradable plastics include both petroleum raw materials and starch produced by agricultural methods. In the Australian context, LCA studies are needed to determine the environmental impacts of biodegradable polymers including their production from raw materials.

11 SOLUTIONS, FUTURE DIRECTIONS AND RESEARCH

Development of Australian Standards and Testing

For the successful introduction of degradable plastics into Australia it is essential that for any new application that the following are clearly identified:

- disposal route;
- appropriate recovery systems;
- processing infrastructure required; and
- the product has been tested against nationally agreed standards to ensure that the disposal route is appropriate and is environmentally sustainable.

For this to be achieved it will be necessary to establish a national framework for standards and testing. This could be based upon appropriate international standards.

Life-Cycle Assessment

Further work is also required to understand the fate and consequence of recalcitrant residues such as small aromatic compounds, small polymer particles and other residues in the environment from the degradation and incomplete degradation of biodegradable plastics.

Full Life Cycle Assessment (LCA) work on the production, use and disposal of biodegradable polymers, with reference to conventional polymers, should be carried out to determine the real environmental and social benefits and impacts of their introduction into a range of applications. This would cover:

- Sources of raw materials (renewable resources, energy and water useage, farming practices, greenhouse gas emissions etc);
- Production of materials;
- Uses and reuses; and
- Disposal environments (including residuals and greenhouse gas potentials).

Comprehensive LCA data and analysis would assist in the development of appropriate policy.

Minimisation of Impact on Reprocessing

The introduction of competing products to those which are currently recovered and reprocessed via sorting facilities, such as some plastics bags, HDPE and PET bottles, should only occur after industry is fully satisfied that failsafe sorting systems are available. As with other plastics, biodegradable polymers could be given a unique polymer identification code to minimise confusion and assist in sorting.

Research on the impacts of the incorporation of biodegradable plastics into established plastics reprocessing systems may be required. Small variations in the ratio of biodegradable to non-biodegradable material could significantly alter the quality of the end material and failure rate in uses reliant on strength. Further research would allow for appropriate policies, labelling, sorting procedures and mechanisms to be developed to minimise the impact on this industry.

Determination of Appropriate Disposal Environments

Extensive consultation with the product supply chain and potential disposal chain, including sorting, reprocessing, and composting bodies, will be necessary before the widespread introduction of biodegradable products that may impact on existing recycling and composting systems. This could be carried out in a similar manner to the National Packaging Covenant and incorporate COAG (Council of Australian Governments) principles.

Composting as a planned disposal route, particularly for film and sheet, should only occur once a system is in place to identify these materials as distinct from non degradable products. One possible solution is to introduce a unique standard colour (i.e. bright lime green) so they can be easily differentiated from non-biodegradable plastics in a composting environment. This way non-biodegradable plastics can still be manually removed while the biodegradable plastics can be left in situ.

Unique colour-based identification of biodegradable plastics would also assist plastic recyclers in identifying those plastics that are not compatible with mechanical recycling processes. A parallel identification system involving a logo such as the ‘Compost OK’ mark would allow consumers to identify these products

There does not appear to be any significant impediment, however, to the introduction of biodegradable products destined for landfill disposal, such as garbage bags, landfill covers, and non-recycled shopping bags, provided that they meet the appropriate testing standards.

Education

With the introduction of biodegradable plastics into the consumer packaging market, effective education is essential. It will be important to educate the public that biodegradable plastics do not degrade instantaneously to avoid the potential to increase the incidence of littering.

In addition, clear disposal routes must be identified and available to consumers to appropriately manage this waste stream. For example, to stipulate that an item should be disposed of to the consumer’s green organics bin which is destined for a commercial composting operation would result in issues where residents are not provided with these services.

12 CONCLUSIONS

The conclusions to the national review of biodegradable plastics are presented below against the Terms of Reference.

Identify the various types and composition of biodegradable plastics available, and likely to be available in Australia

Over the last few years there has been a significant expansion in the range of biodegradable plastics which are commercially available or are under commercial development. This trend is expected to continue. The range of biodegradable plastics available include:

- Starch based products including thermoplastic starch, starch and synthetic aliphatic polyester blends, and starch and PVOH blends.
- Naturally produced polyesters including PVB, PHB and PHBH.
- Renewable resource polyesters such as PLA.
- Synthetic aliphatic polyesters including PCL and PBS.
- Aliphatic-aromatic (AAC) copolyesters.
- Hydro-biodegradable polyester such as modified PET.
- Water soluble polymer such as polyvinyl alcohol and ethylene vinyl alcohol.
- Photo-biodegradable plastics.
- Controlled degradation additive masterbatches.

There is an extensive range of potential applications. Some of these include:

- Film including overwrap, shopping bags, waste and bin liner bags, composting bags, mulch film, silage wrap, body bags/coffin liners, landfill covers, packaging – incl.O_2 & H_2O barriers, bait bags, nappy backing sheet, and cling wrap.
- Flushable sanitary products.
- Sheet and non woven packaging.
- Bottles.
- Liquid paper board.
- Planter boxes and fishing nets.
- Food service cups, cutlery, trays, and straws.
- Loose fill foam.

Whilst some biodegradable plastics are used for some of these applications in Europe, the current market penetration into Australia is low. This is generally limited to some films including landfill cover, food service cups, cutlery and trays, and loose fill foam. There have also been trials of other applications such as shopping bags, mulch film, EVOH bottles and bait bags.

Identify standards and test methods for biodegradable plastics in Australia

There are currently no Australian standards and test methods for biodegradable plastics. There is a need to establish Australian Standards that match the potential application areas and disposal environments in Australia.

Internationally, there are several standards that could be applied, or adapted, to meet the requirements of the Australian market place. The most comprehensive appears to be the various ASTM standards and test methods. These address the various degradation methods and a range of disposal environments.

There are also several standards for compost derived products including the Australian Standard AS 4454-1999 Compost Soil Conditioners and Mulches, as well as standard testing procedures for plant and animal toxicity.

Examine the range of disposal methods and identify the most frequent disposal option for each biodegradable plastic application at end of life

The major disposal environments for biodegradable plastics are:

- composting facilities or soil burial;
- anaerobic digestion;
- wastewater treatment facilities;
- plastics reprocessing facilities;
- landfill;
- marine and freshwater environments; and
- general open environment as litter.

To a large extent, the nature of the biodegradable plastic application should dictate the disposal environment. Further LCA studies are required to determine appropriate disposal routes for different polymers and products.

The most common, and perhaps desirable, method of disposal is composting as this results in the production of a useful end product. Landfill disposal, particularly for garbage bags is also a significant disposal route. Wastewater treatments plants are only suitable for flushable products that have an extremely rapid degradation rate. There has been some development work with bait bags and fishing lines although the results are not conclusive. As with flushable products a rapid degradation rate is required.

Despite community education programmes and enforcement, litter will continue to be a disposal route for biodegradable as well as degradable plastics.

Identify current technologies to avoid contamination and sort biodegradable plastics in Australia and overseas

The risk of contamination by biodegradable plastics of conventional plastics which are currently recycled and reprocessed, from both kerbside and industrial recycling systems, is a significant one. This could result in changing the characteristics of the material and may lead to a failure of products as degradation occurs. Even a minor increase in failure would be significant in many applications. The growing confidence in recycled plastics could be eroded if technical integrity is comprised.

There are a range of measures to sort different polymers. Initially this is a manual exercise relying on sorting staff being able to recognise and differentiate items based on knowledge of material use in different product categories. This is then backed up at some plastics reprocessors with sorting technologies based on specific gravity or optical sorting equipment. This is difficult when biodegradable plastics have similar physical properties to reyclable plastics.

The best technology to sort biodegradable plastics from non-biodegradable plastics may be near infra-red (NIR) detection which can be used in a positive sort system. The NIR system can be tuned for example to positively sort starch-based polymers and in this way a pure biodegradable stream could be segregated for composting. The viablity of NIR detection systems at a commercial scale is beyond the scope of this review.

Describe and assess the environmental impacts arising from the foreseeable increase in use of biodegradable plastics in various applications

There are several identifiable environmental benefits that may potentially be derived from the use of biodegradable plastics compared to conventional petroleum-based plastics. These are:

- Compost derived in part from biodegradable plastics increases the soil organic content as well as water and nutrient retention, while reducing chemical inputs and suppressing plant disease.
- Biodegradable shopping and waste bags disposed of to landfill may increase the rate of organic waste degradation in landfills while enhancing methane harvesting potential and decreasing landfill space usage. Biodegradable landfill covers may also considerably extend landfill life.
- The energy required to synthesise and manufacture biodegradable plastics is generally much lower for most biodegradable plastics than for non-biodegradable plastics. The exception is PHA biopolymers which consume similar energy inputs to polyethylenes. New feedstock for PHA should lower the energy required for their production.
- Biodegradable plastics also offer important environmental benefits through, in many cases, the use of renewable energy resources and reduced greenhouse gas emissions.

Biodegradable plastics also pose some adverse environmental risks. These include:

- Pollution in waterways due to high BOD concentrations resulting from the breakdown of starch-based biodegradable plastic.
- Migration of plastic degradation by-products such as residual pigments, catalyst residues and isocyanate via run-off and leachate from landfills and composting facilities to groundwater and surface water bodies.
- Trauma and death of marine species resulting from only partial or slow degradation of biodegradable plastic products in marine environments.
- Possible increase in the incidence of littering due to the belief that biodegradable plastics will disappear quickly.
- Soil and crop degradation resulting from the use of compost that may have unacceptably high organic and or metal contaminants derived from biogegradable plastic residuals, additives and modifiers such as coupling agents, plasticisers, fillers, catalysts, dyes and pigments.

Identify possible and existing solutions to identified impacts and limitations

For the successful introduction of degradable plastics into Australia it is essential that for any new application that the following are clearly identified:

- disposal route;
- appropriate recovery systems;
- processing infrastructure required; and
- the product has been tested against nationally agreed standards to ensure that the disposal route is appropriate and is environmentally sustainable.

For this to be achieved it will be necessary to establish a national framework for standards and testing. This can be based upon appropriate international standards. It is recommended that the Federal Government, through Environment Australia and in consultation with the plastics industry, take an initiating role in undertaking further research and developing these standards.

Further research focus areas include:

- Life-cycle assessment;
- Minimisation of the impacts on reprocessing;
- Determination of appropriate disposal methods; and
- Consumer education.

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14 REPORT LIMITATIONS

This report has been prepared in accordance with an agreement between Environment Australia and Nolan-ITU.

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This report is solely for the use of Environment Australia and any reliance of this report by third parties shall be at such party's sole risk and may not contain sufficient information for purposes of other parties or for other uses. This report shall only be presented in full and may not be used to support any other objectives than those set out in the report, except where written approval with comments are provided by Nolan-ITU.

Appendix A

GLOSSARY

Abiotic disintegration

Disintegration of plastic materials by means other than by biological process such as dissolution (dissolving), oxidative embrittlement (heat ageing) or photolytic embrittlement (UV ageing).

Activated Sludge

Sludge with active, live degradation micro-organisms.

Aerobic degradation

Aerobic degradation is degradation in the presence of air (oxygen). Essentially aerobic degradation is composting. Aerobic degradation of plastics under controlled composting conditions is described in ASTM 5338-92.

Aliphatic-aromatic Copolyesters (AAC)

These copolymers combine the excellent material properties of aromatic polyesters (e.g. PET) and the biodegradability of aliphatic polyesters. They are soft, pliable and have good tactile properties. Melting points are high for a degradable plastic (around 200°C).

Aliphatic polyesters (e.g. PCL)

Aliphatic polyesters are biodegradable but often lack in good thermal and mechanical properties. While, vice versa, aromatic polyesters (like PET) have excellent material properties, but are resistant to microbial attack. Typical aliphatic polyesters include polyhydroxy butyrate, polycaprolactone, polylactic acid and polybutylene succinate. Aliphatic polyesters degrade like starch or cellulose to produce non-humic substances such as CO_2 and methane. They can be processed on conventional processing equipment at 140-260 °C, in blown and extruded films, foams, and injection moulded products.

Amylose

A component of starch consisting of a chain polymer of linked D-glucopyranosyl structures. Thermoplastic starch polymers consist largely of amylose.

Anaerobic degradation

Degradation in the absence of air (oxygen) as in the case of landfills. Anaerobic degradation is also called biomethanization. Anaerobic degradation of plastics can be determined by measuring the amount of biogas released as described in ASTM 5210-91.

ASTM

The American Society of Testing and Materials

Bioassimilation

Chemical assimilation of a substance into the natural environment (see also mineralization)

Biodegradable

The ASTM defines biodegradable as “capable of undergoing decomposition into carbon dioxide, methane, water, inorganic compounds, or biomass in which the predominant mechanism is the enzymatic action of microorganisms, that can be measured by standardized tests, in a specified period of time, reflecting available disposal condition.” It is important to note that the definition of biodegredation should specify a time limit. If the biodegradation process is sufficient to mineralise organic matter into carbon dioxide or methane respectively, water and biomass, the material can be termed “biodegradable”.

Bioerodable

Polymers that exhibit controlled degradation through the incorporation of prodegradant additive masterbatches or concentrates. Such polymers oxidize and embrittle in the environment and erode under the influence of weathering.

Biomass

The weight of all the organisms in a given population, trophic level or region.

Compostable

Compostable is defined as ‘capable of undergoing biological decomposition in a compost site as part of an available program, such that the plastic is not visually distinguishable and breaks down to carbon dioxide, water, inorganic compounds, and biomass, at a rate consistent with known compostable materials (e.g. cellulose).’ A polymer is “compostable” when it is biodegradable under composting conditions.

Compostable Plastics

A polymer is ‘compostable’ when it is biodegradable under composting conditions. The polymer must meet the following criteria:

a) Break down under the action of micro-organisms (bacteria, fungi, algae).

b) Total mineralisation is obtained (conversion into CO_2, H_2O, inorganic compounds and biomass under aerobic conditions).

c) The mineralisation rate is high and is compatible with the composting process.

The degree of degradability of the material shall be measured under controlled composting conditions as per ASTM D 5338-92. Those materials having a degree of biodegradation equivalent to that of cellulose (maximum permissible tolerance of 5%) will be considered to meet the compostability criteria.

Composting

Breaking down of plant and animal material using micro-organisms under aerobic conditions. For successful composting there must be sufficient water and air to allow the micro-organisms to break down the material. The U.S. EPA defines composting as ‘the controlled decomposition of organic matter by microorganisms into a stable humus material.’

Copolyesters

Copolyesters combine aromatic esters with aliphatic esters or other polymer units (e.g. ethers and amides) and thereby provide the opportunity to adjust and control the degradation rates.

Decomposer organism

An organism, usually a bacterium or a fungus, that breaks down organic material into simple chemical components, thereby returning nutrients to the physical environment.

Degradability

Ability of materials to break down, by bacterial (biodegradable), thermal (oxidative) or ultraviolet (photodegradable) action. When degradation is caused by biological activity, especially by enzymatic action, it is called ‘biodegradation’.

Degradable PET

Up to three aliphatic monomers can be incorporated into the PET structure to create weak spots in the polymeric chains that make them susceptible to degradation through hydrolysis.

Ecotoxicity

Ecotoxicity refers to the potential environmental toxicity of residues, leachate, or volatile gases produced by the plastics during biodegradation or composting

Foamed starch

Starch can be blown by environmentally friendly means into a foamed material using water steam. Foamed starch is antistatic, insulating and shock absorbing, therefore constituting a good replacement for polystyrene foam.

Functional Group

A particular grouping of elements in a molecule or compound which gives it particular properties, such as physical properties or the ability to undergo certain chemical reactions.

Humus

The organic substance that results from decay of plant or animal matter. Humus results from the degradation of lignin, carbohydrate, and proteins. Biodegradable plastics can form humus as they decompose. The addition of humus to soil is beneficial.

Hydrolysis

Hydrolysis refers to the cleavage or breakage of bonds by reaction with water or moisture. All polyesters degrade eventually, with hydrolysis being the dominant mechanism.

LCA

Life Cycle Assessment.

Masterbatch

A concentrate of additive in a polymer-based carrier resin. A masterbatch is generally added to a polymer in order to introduce various additives at a known level.

Mineralisation

Conversion of a biodegradable plastic to CO_2, H_2O, inorganic compounds and biomass. For instance the carbon atoms in a biodegradable plastic are transformed to CO_2 which can then re-enter the global carbon cycle.

Modified PET

Polyethylene Tetraphalate (PET) id a rigid polymer to which alphatic monomers can be added to enhance biodegradability, such as PBAT (polybutylene adipate/terephthalate) and PTMAT (polytetramethylene adipate/terephthalate).

Monomer

A molecule that can join with other molecules to form a large molecule called a polymer. A monomer is the smallest repeating unit in a polymer chain.

Organic Recycling

Organic recycling is defined as aerobic (ie. composting) or anaerobic (bio-methanisation) treatment of the biodegradable parts of plastic packaging under controlled conditions using micro-organisms to produce stabilised organic residues, methane and carbon dioxide.

Photo-biodegradation

Degradation of the polymer is triggered by UV light and assisted by the presence of UV sensitisers. In this process the polymer is converted to low molecular weight material (waxes) and in a second step converted to carbon dioxide and water by bacterial action.

Photodegradable

A process where ultraviolet radiation degrades the chemical bond or link in the polymer or chemical structure of a plastic.

Phytotoxicity

Phytotoxicity refers to toxic effects on plants. Plant phytotoxicity testing on the finished compost that contains degraded polymers can determine if the buildup of inorganic materials from the plastics are harmful to plants and crops and if they slow down soil productivity.

Plastified Starch

See Starch Composites (50 % Starch)

Polybutylene succinate (PBS) and polybutylene suucinate adipate (PBSA)

Biodegradable synthetic aliphatic polyesters. Adipate co-polymers are added to the PBS polymer to make its use more economical.

Polycaprolactone (PCL)

Polycaprolactone is a biodegradable thermoplastic polymer derived from the chemical synthesis of crude oil. Although not produced from renewable raw materials, it is fully biodegradable.

Polyesters

Polymers with ester groups in their backbone chains. All polyesters degrade eventually, with hydrolysis being the dominant mechanism. Degradation rates range from weeks for aliphatic polyesters (e.g. polyhydroxyalkanoates) to decades for aromatic polyesters (e.g. PET).

Polyhydroxyalkanoates (PHA)

PHAs are linear aliphatic polyesters produced in nature by bacterial fermentation of sugar or lipids. More than 100 different monomers can be combined within this family to give materials with extremely different properties. They can be either thermoplastic or elastomeric materials, with melting-points ranging from 40 to 180°C. The most common type of PHA is PHB (poly-beta-hydroxybutyrate).

Polyhydroxybutyrate (PHB)

PHB has properties similar to those of polypropylene, however it is stiffer and more brittle.

Polyhydroxybutyrate-valerate copolymer (PHBV)

Polyhydroxybutyrate-valerate is a PHB copolymer which is less stiff and tougher, and it is used as packaging material.

Polylactic Acid (PLA)

A biodegradable polymer derived from lactic acid. PLA resembles clear polystyrene, it provides good aesthetics (gloss and clarity), but it is stiff and brittle and needs modification for most practical applications (e.g. plasticisers increase its flexibility).

Polylactic acid aliphatic copolymer (CPLA)

Biodegradable CPLA is a mixture of polylactic acid and other aliphatic polyesters. It can be either a hard plastic (similar to PS) or a soft flexible one (similar to PP) depending on the amount of aliphatic polyester present in the mixture.

Polymer

A long molecule that is made up of a chain of many small repeated units (monomers).

Polyvinyl Alcohol (PVOH)

Polyvinyl alcohol is a synthetic, water-soluble and readily biodegradable polymer.

Prodegradant

An additive that can trigger and accelerate the degradation of a polymer. Typically prodegradants (or degradation promoters) are catalytic metal compounds based on iron, cobalt and manganese.

Recalcitrant Residues

Non-biodegradable residues that remain after partial or incomplete biodegradation of a 'biodegradable' plastic. The recalcitrant organics are the compounds that show resistance to biodegradation. Most of the synthetic polymers exhibit the phenomenon of recalcitrance because of dissimilar chemical structures to those of naturally occurring compounds

Starch Composites (10 % Starch)

Starch can be used as a biodegradable additive or replacement material in traditional oil-based commodity plastics. If starch is added to petroleum derived polymers (e.g. PE), it facilitates disintegration of the blend, but not necessarily biodegradation of the polyethylene component. Starch accelerates the disintegration or fragmentation of the synthetic polymer structure. Microbial action consumes the starch, thereby creating pores in the material which weaken it and enable it to break apart.

Starch Composites (50 % Starch)

Also called plastified starch materials. Such materials exhibit mechanical properties similar to conventional plastics such as PP, and are generally resistant to oils and alcohols, however, they degrade when exposed to hot water. Their basic content (40-80%) is corn starch, a renewable natural material. The balance is performance-enhancing additives and other biodegradable materials.

Starch Composites (90 % Starch)

Usually referred to as thermoplastic starch. They are stable in oils and fats, however depending on the type, they can vary from stable to unstable in hot/cold water. They can be processed by traditional techniques for plastics.

Thermoplastic Polymers

Becomes soft and 'plastic' upon heating and firm when cool, with this process able to repeated without the material becoming brittle.

Thermosetting Polymers

Sets firmly and cannot be heated plastic again.

Thermoplastic Starch

See Starch Composites (90 % Starch)