The impacts of degradable plastic bags in Australia

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ACRONYMS

CO₂ - carbon dioxide
H₂O - water
Ce – cerium
Co – cobalt
Cu - copper
Fe – iron
HDPE – high density polyethylene
LDPE – low density polyethylene
LLDPE – linear low density polyethylene
Mn – manganese
Ni – nickel
PE – polyethylene
PP - polypropylene
PS - polystyrene
PLA - polylactic acid
PCL – polycaprolactone
PBS - polybutylene succinate
PBSA - poly (butylene succinate-co-adipate)
PBAT - polybutyrate adipate terephthalate
PHB - polyhydroxybutyrate
PHBV - polyhydroxybutyrate blended with poly - (3-hydroxy-butyrate-valerate)
EXECUTIVE SUMMARY

The Department of the Environment and Heritage on behalf of the Environment Protection and Heritage Council (EPHC) commissioned this study, to investigate the full impacts of introducing degradable plastic bags in the Australian market.

Types of degradable plastics

Degradable plastics are designed to degrade in different ways and in different environments. There are many different types of degradable plastics being introduced into the Australian market at present, resulting in confusion about their impacts and benefits. An important distinction needs to be made between biodegradable plastics, i.e. those that capable of undergoing decomposition into carbon dioxide, methane, water, inorganic compounds, or biomass in which the predominant mechanism is the enzymatic action of microorganisms (bacteria, fungi, algae), and oxo-biodegradable plastics, which oxidize and embrittle in the environment and erode under the influence of ultraviolet (UV) light and heat.

Critical issues for degradability

The impacts of degradable polymers at end-of-life depend on the characteristics of the polymer itself (i.e. what the polymer is made from and how it is designed to degrade), the thickness and surface area of the product, as well as the disposal environment. There are insufficient data to say with any certainty, how long many degradable polymers take to fully biodegrade, and the impacts of any end products in the environment.

Biodegradable plastics including starch based polymers and polyesters, are designed to break down under composting conditions, i.e. through the actions of microorganisms. This makes them ideally suited to products that will be collected as part of a source-separated organics collection, e.g. green and food waste bags collected from households.

Oxo-biodegradable polymers (with prodegradant additives) are designed to break down under the influence of heat and UV light. Final biodegradation takes place through the action of microorganisms, although there still appears to be some uncertainty about the time needed to fully degrade (particularly whether it can occur within the normal commercial composting period) and the environmental impacts of plastic fragments and additives.

The advantages of degradable polymers in landfill are questionable. Minimal degradation of organic materials (including food and green waste) takes place in controlled dry landfills. In wet landfills, degradation is more likely to take place, but degradation of organic materials could have negative impacts on greenhouse gas generation¹ and contamination of groundwater with

¹ Gases escape to the atmosphere while the landfill is being filled (before capping); a small percentage escapes even while gas is being collected; and some gas continues to be generated after the gas recovery system has been
The use of biodegradable or oxo-biodegradable polymers for products that are designed for disposal in landfill will result in a loss of resources as the products will not be recovered through either composting or recycling, and will have very little impact on the quantity of waste to landfill or the life of landfills.\(^2\)

**Life cycle impacts of degradable bags**

A streamlined Life Cycle Assessment (LCA) was undertaken for bags manufactured from degradable polymers. These were compared with conventional HDPE bags, paper bags, reusable plastic bags and calico bags.

The LCA concluded that **reusable bags have lower environmental impacts than all of the single-use bags**, including both conventional HDPE bags and degradable bags.

**Degradable plastics in the litter stream**

Degradable polymers could potentially reduce the visual impacts of plastic bags in the litter stream. The bags will disintegrate relatively quickly if exposed to heat, UV light, mechanical stress and/or water, but will not biodegrade in the absence of microorganisms. As plastic bags may take some time to come into contact with microorganisms, particularly on land, there is uncertainty about the time any product will take to completely biodegrade. There is also insufficient evidence to say whether degradable bags will have a positive or negative impact on littering behaviour.

The potential impacts on fish and other marine life are not clear – while disintegration of plastics into smaller pieces may make them less likely to be ingested by larger animals, smaller pieces might make them more attractive to smaller animals such as sea turtle hatchlings.

**Recycling or degradability**

Many plastics recyclers are concerned that degradable products and their additives will contaminate batches of recycled resins. Degradable plastics by their very nature are designed to break down under the influence of heat, light and/or moisture. Given this, **degradable plastics have the potential to interfere with the processing of recovered polymers and to**

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\(^2\) Shopping bags only make up around 2.5% of total plastics, or 1% of total packaging, consumed in Australia each year (Nolan-ITU et al 2002: 25). Even if all bags were made from 100% degradable resins they are unlikely to biodegrade completely in landfill due to the less than ideal conditions. The overall impact will therefore be minimal.
destabilize and compromise the properties of recycled polymers if they enter the plastics recycling stream.

The revised Code of Practice for Shopping Bags is likely to include a 15% recycling target for HDPE shopping bags if collection is only from supermarkets, and 30% if bags are also collected from kerbside. The choice for retailers and bag manufacturers appears to be either to pursue a recycling strategy or a composting strategy for the bags – not both. Degradable bags have potential to reduce the quality of recyclate from plastic bags and to therefore undermine plastics recycling programs.

Giving the market certainty - dialogue, standards and certification

Since the range of degradable polymer options is expected to increase in coming years there is a pressing need to develop an Australia Standard for degradable plastics. A system for certification of plastics that meet this standard is also critically important.

An Australian Standard for degradable plastics should address the following areas:

- Provision of test methods that enable both the biodegradation and oxo-biodegradation of the degradable plastic to be validated;
- A system for certification of degradable polymers that conform to the standard (e.g. the system used for EN 13432);
- The standard should give coverage to the range of potential application areas and disposal environments in Australia;
- The standard should not be so severe as to exclude kraft paper as do some European standards;
- The standard should be developed with reference to the existing international standards. The standard should differentiate between biodegradable and other degradable plastics (as does ASTM D6400);
- Clarification between biodegradation and abiotic disintegration even if both systems demonstrate that sufficient disintegration of the plastic has been achieved within the specified testing time;
- The standard should address environmental fate and toxicity issues (as does ASTM D5152); and
- The standard should sensibly answer the debate on whether total mineralization is required (i.e. the conversion into carbon dioxide, water, inorganic compounds and biomass under aerobic conditions) or whether disintegration (into fine visually

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3 Degradable plastics can in theory be kept out of the recycling stream, through colour coding of degradable bags and consumer education. In practice it would be difficult to achieve if degradable and non-degradable bags are both used by the same community.
indistinguishable fragments) and partial mineralization that is compatible with the composting process is adequate.

Another useful process for taking the issue forward could be to set up a covenant framework for the introduction of degradable plastics into Australia. This could be used to initiate a dialogue between the key players (manufacturers, retailers, governments, and consumers) on the issue of how to introduce degradable plastics into Australia to maximise environmental benefits across all sectors.
1 Introduction

1.1 Aim of the project
The Department of the Environment and Heritage on behalf of the Environment Protection and Heritage Council (EPHC) commissioned this study, to investigate the full impacts of introducing degradable plastic bags in the Australian market. In particular, it aimed to examine the effects on national recycling efforts, local manufacturing, and landfills.

The work undertaken for this report builds on previous studies for the Department of the Environment and Heritage, including:

- *Biodegradable Plastics – Developments and Environmental Impacts* (Nolan-ITU and ExcelPlas Australia 2002); and

1.2 Research questions
This study has attempted to answer several important research questions about degradable bags:

- What are the potential impacts of degradable plastic bags in different disposal environments including landfill, commercial composting, home composting, litter and recycling?
- What are the environmental impacts of degradable plastic bags over their total life cycle, for example on materials efficiency?
- Will the introduction of degradable plastic bags reduce the litter problem?
- Will they have any negative impacts on plastics recycling systems?
- What are the potential impacts on industry and consumers of introducing degradable bags?
- What are the most appropriate applications for degradable bags in the Australian context?
- What steps need to be taken to support successful use of degradable bags, including preparatory work for an Australian Standard?

1.3 Scope
For the purpose of this report, plastic bags are defined as supermarket and retail shopping bags, green waste / compost bags, bin liners, fruit bags / mesh, bait bags, bread and ice bags; with the main focus on shopping carry bags.

1.4 Methodology
The methodology for the project included:
• A detailed international literature review;
• Interviews with manufacturers, importers, recyclers and retailers;
• A focus group of consumers in Melbourne; and
• A streamlined Life Cycle Assessment (LCA) of four degradable polymers.

Interviews were conducted in person or by telephone in July and August 2003. The focus group involved 10 people in Melbourne; including 3 men and 7 women ranging in age between 25 and 45, and from a range of household type (single, group house, families with small children and teenagers, divorced with part time child care). It was conducted at RMIT on the evening of 6 August 2003 for one and a half hours. The focus group was not intended to provide representative data, but rather to test ideas and suggest directions for further quantitative and qualitative consumer research.

The streamlined LCA compared life cycle impacts of six degradable materials for shopping bags with conventional HDPE shopping bags and reusable plastic, paper and calico bags. The six degradable polymers were selected on the basis of their suitability for the manufacture of shopping bags and the availability of reliable data. Data was obtained from previously published research.

The LCA was undertaken using the LCA software package SimaPro 5.1. Australian data was used for energy production, some material production (e.g., PET, HDPE), transport, recycling and waste disposal (Grant et al. 2001; Grant et al. 2003a). International public data was used to model the remaining materials. A streamlined LCA has limitations in that all data points across a particular life cycle are not all included, though it does provide a scoping of the issues taking a life cycle perspective.
2 Overview of degradable polymers

This section includes an overview of:

- The types of environmentally degradable plastics that are suitable for the manufacture of functional plastic bags; and
- The degradation pathways and known or likely degradation products of common classes of degradable plastics that are suitable for the production of consumer plastic bags.

Degradability is the ability of materials to break down, by bacterial (biodegradable), thermal (oxidative) or ultraviolet (photodegradable) action.

In order for degradable polymers to be made into functional plastic bags they must meet the following criteria:

- Be able to be formed into film;
- Have adequate tensile strength and elongation;
- Have adequate puncture resistance;
- Have adequate tear resistance (not too splitty); and
- Generally possess properties that resemble low-density polyethylene (LDPE) or high-density polyethylene (HDPE) in overall physical properties and rheological characteristics.

It is also evident that degradable plastics for bags are required to degrade rapidly at the end of their useful life while it is equally important that their mechanical properties remain essentially unchanged during use.

In general, it is essential that the polymer retain its useful properties through one or more of a variety of fabrication procedures, e.g., blending, pelletising, extrusion, blown or cast film fabrication. The final product – film/ bag– must have a reasonable storage and reuse life. Additionally, the customer expects to have functional bags that serve a useful purpose under a variety of circumstances. It is only at the end of the service life that the polymer must degrade in the disposal environment.

In summary, there are three essential criteria for biodegradation of plastic bags:

- They must disappear and leave no visible trace;
- This disintegration must occur in a reasonable timeframe (e.g. 3 months or 6 months); and
- They must not leave behind any toxic residues.
2.1 Types of degradable plastic bags
Degradable bags can be classified in two ways:

- According to the way that they degrade, for example whether they require the actions of microorganisms (i.e. are biodegradable), or whether they require heat, ultraviolet light, mechanical stress or water in order to break down; and

- According to the materials they are manufactured from, for example whether they are made from natural starch polymers, from synthetic polymers or from a blend of a conventional polymer with an additive to facilitate degradation.

Polymers can degrade in a number of different ways, for example they can be biodegradable, oxo-biodegradable, photodegradable or water-soluble. Descriptions of each type of degradation are provided below:

- **Biodegradable polymers** are those that are capable of undergoing decomposition into carbon dioxide, methane, water, inorganic compounds or biomass in which the predominant mechanism is the enzymatic action of microorganisms, that can be measured by standardized tests, in a specified time, reflecting available disposal conditions.

- **Compostable polymers** are those that are degradable under composting conditions. To meet this definition they must break down under the action of microorganisms (bacteria, fungi, algae), achieve total mineralization (conversion into carbon dioxide, methane, water, inorganic compounds or biomass under aerobic conditions) and the mineralization rate must be high and compatible with the composting process.

- **Oxo-biodegradable polymers** are those that undergo controlled degradation through the incorporation of ‘prodegradant’ additives (additives that can trigger and accelerate the degradation process). These polymers undergo accelerated oxidative define degradation initiated by natural daylight, heat and/or mechanical stress, and embrittle in the environment and erode under the influence of weathering.

- **Photodegradable polymers** are those that break down through the action of ultraviolet (UV) light, which degrades the chemical bond or link in the polymer or chemical structure of the plastic. This process can be assisted by the presence of UV-sensitive additives in the polymer.

- **Water-soluble polymers** are those that dissolve in water within a designated temperature range and then biodegrade in contact with microorganisms.

The composition of degradable bags also varies, with the main categories being:

- **Thermoplastic starch-based polymers** made with at least 90% starch from renewable resources such as corn, potato, tapioca or wheat.
• **Polyesters** manufactured from hydrocarbons (oil or gas). All polyesters degrade eventually, with degradation rates ranging from weeks for aliphatic polyesters (e.g. polyhydroxyalkanoates) to decades for aromatic polyesters (e.g. PET).

• **Starch – polyester blends** that mix thermoplastic starch with polyesters made from hydrocarbons.

Table 1 provides a list of the different types of degradable polymers. This table classifies polymers according to both degradation pathway and composition, and lists some of the commercial products available in each category.
<table>
<thead>
<tr>
<th>Polymer category, degradation pathway</th>
<th>Composition</th>
<th>Commercial examples</th>
<th>From renewable or non-renewable resources</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Biodegradable starch-based polymers</strong></td>
<td>Thermoplastic starch derived from corn, potato or wheat, blended with additives (e.g. plasticizers)</td>
<td>Novon (Novon International, USA) Eco-FOAM (National Starch) Paragon (Avebe)</td>
<td>Mostly renewable</td>
</tr>
<tr>
<td></td>
<td>Thermoplastic starch derived from corn, potato or wheat, blended with polyester (PLA or PCL)</td>
<td>Mater-Bi™ (Novomont, Italy) BioFlex™</td>
<td>Starch component renewable, but hydrocarbon-based plastics and energy for agriculture are non-renewable.</td>
</tr>
<tr>
<td></td>
<td>Thermoplastic starch derived from tapioca, corn, potato or wheat, blended with polyethylene</td>
<td>Earthstrength (Lloyd Brooks) Polystarch N (Willow Ridge) Entec (EAM, India) Environmentally Degradable Plastic (MEBI, China)</td>
<td>As above</td>
</tr>
<tr>
<td></td>
<td>Thermoplastic starch derived from corn, blended with PVOH</td>
<td>Plastic (Plantic Technologies, Aust.)</td>
<td>As above</td>
</tr>
<tr>
<td><strong>Biodegradable polyesters</strong></td>
<td>Polybutylene succinate (PBS)</td>
<td>Sky Green™ (SK Polymers, Korea) Bionelle (Showa Highpolymer, Japan)</td>
<td>Non-renewable</td>
</tr>
<tr>
<td></td>
<td>Poly (butylene succinate-co-adipate) (PBSA) copolymers</td>
<td>Sky Green™ (SK Polymers, Korea)</td>
<td>Non-renewable</td>
</tr>
<tr>
<td></td>
<td>Polybutyrate adipate terephthalate (PBAT))</td>
<td>Bionelle (Showa Highpolymer, Japan)</td>
<td>Non-renewable</td>
</tr>
<tr>
<td></td>
<td>Adipic acid aliphatic/aromatic copolyesters (AAC)</td>
<td>EcoFlex™ (BASF) Eastar Bio™ (Eastman)</td>
<td>Non-renewable</td>
</tr>
<tr>
<td></td>
<td>Polylactic acid (PLA)</td>
<td>Nature-Works (Cargill-Dow) Lacea (Mitsui Toatsu) Lucty (Shimazu) Galactic (Galactic)</td>
<td>Renewable</td>
</tr>
<tr>
<td></td>
<td>Polycaprolactone (PCL)</td>
<td>Tone (Union Carbine, USA) CAPA (Solvay, Belgium) Placeel (Daicel Chemical Indus., Japan)</td>
<td>Non-renewable</td>
</tr>
<tr>
<td></td>
<td>Polyhydroxy-butyrate-valerate) (PHB/V)</td>
<td>Biopol (was Monsanto) Biomer (Biome)</td>
<td>Renewable</td>
</tr>
<tr>
<td></td>
<td>Blends of PHB with PCL</td>
<td>Capron</td>
<td>Combination renewable and non-renewable</td>
</tr>
<tr>
<td></td>
<td>Modified PET</td>
<td>Biomax</td>
<td>Non-renewable</td>
</tr>
<tr>
<td><strong>Controlled degradation masterbatch</strong></td>
<td>Polyethylene with a thermal and/or UV prodegradant additive</td>
<td>TDPA (EPI) Totally Degradable Plastic™ (Symphony Environmental)</td>
<td>Non-renewable</td>
</tr>
</tbody>
</table>
2.1.1 Starch-based polymers

Thermoplastic starches are based on gelatinized starch from potato, corn, wheat or tapioca. With the use of specific plasticizing solvents they can produce thermoplastic materials with good performance properties and with inherent biodegradability. Importantly, thermoplastic starch compounds can be processed on existing plastics fabrication equipment.

Three generations of starch-based polymers have been developed. The first generation consists of a synthetic polymer, usually polyethylene (PE), and the starch is only present as a filler. These bags are not fully biodegradable and consist of mainly non-biodegradable synthetic polymers like polyethylene or polypropylene and only 5-30 percent starch. Under special conditions the starch degrades and the plastic disintegrates into small particles that will persist for many years although they are not visible.

A number of companies are marketing starch – PE blends, including Lloyd Brooks (Earthstrength), EAM and MEBI. Earthstrength uses tapioca starch-based resin, which is added to PE at a ratio of around 30%. MEBI refer to their product as a ‘starch-based additive’, which can be added to PE, polypropylene (PP) or polystyrene (PS) at ratios of 5-50% depending on the speed of degradation required. Similarly, EAM describe their product as a ‘biodegradable plastic additive’ made from starch, and suggest quantities of 15-50% should be added depending on degradation requirements. Both MEBI and EAM refer to their product as being ‘photo-biodegradable’.

In the second generation the thermoplastic starch is used for its polymeric properties. It is blended with hydrophilic synthetic polymers (e.g. Bionelle™ which is an aliphatic polyester or polycaprolactone) and contributes to the strength of the material. About 50-80% starch can be used in these plastics, but still a large part is not from renewable resources.

The third generation is a truly biodegradable plastic that does not contain synthetic polymers at all. To improve some of the properties of the plastic, the biopolymer may be modified, but no synthetic materials are necessary, for example Novon, which is starch (90-95%) plus additives.

One example of the first generation products but with refinements is the Willow Ridge products such as PolyStarch N, a masterbatch of 55% cornstarch with LLDPE. The product includes a
processing aid and 3-10% levels of a desiccant (trade-named Aquanil) that ensures moisture control prior to use. PolyStarch N is suitable for LDPE and LLDPE garbage bags, agricultural films, and injection and blow molded parts intended for disposal in conditions able to sustain microbes.

### 2.1.2 Starch-Polyester Blends

Bags of starch/synthetic polyester/starch blends have been produced. These can be based on polybutylene succinate or polybutylene succinate adipate. A small amount (5% by weight) of compatibilizer (maleic anhydride functionalized polyester) is generally added to impart phase stability (to improve miscibility). At higher starch content (>60%), such bags can be brittle. For this reason plasticizers are also added to reduce the brittleness and improve flexibility. The BioBag™ is made from the Novamont resin that has been around since 1994, and is made from starches (maize) in combination with fully biodegradable aliphatic polyesters, aliphatic/aromatic polyesters or in particular polylactic acid.

A common biodegradable polyester that is often used in combination with starch to produce plastic bags is Ecoflex™ (BASF). Ecoflex™ is a statistical aliphatic-aromatic copolyester based on 1,4-butanediol and the dicarboxylic acids, adipic acid and terephthalic acid. Its proper name is poly (tetramethylene adipate-co-terephthalate).

In a commercial biodegradable bag application the polyester is generally blended with equal parts of thermoplastic starch (such as the EcoFlex product). The ratio of base components is anticipated to be:

- 12.5% terephthalic acid
- 12.5% adipic acid,
- 25% 1,4- butanediol
- 50% high amylose starch

Biodegradable plastics based on aliphatic/aromatic copolyesters, especially those synthesized from butanediol, adipic acid and terephthalic acid contain approximately 30-55 mol% terephthalic acid in the acid components of the copolymers (Muller et al. 1998).

Bionelle (Showa Highpolymer Co., Ltd., Tokyo, Japan) is based on the ester of succinic acid/adipic acid and 1,4-butanediol is used to make this biodegradable polymer. The ratio of base components is estimated to be:

- 12.5% succinic acid
- 12.5% adipic acid,
- 25% 1,4- butanediol
- 50% high amylose starch

The earlier biodegradable plastic bags offered by Mater-Bi™ were based on a blend of thermoplastic starch and polycaprolactone (PCL) however this blend had a low softening point
and also PCL is only available in bulk quantities from one supplier (Union Carbide). Around 2001 a switch was made to blends of starch and other polyesters. These blends exhibit higher softening points and clarity comparable to LLDPE. Newer grades of these blends have even better optical properties (such as low haze and higher gloss) (Hall 2003). Bio-Corp bags (made from Mater-Bi™) were used at the 2000 Sydney Olympics (Hall 2003).

Thermoplastic starch combined with hydrophobic biodegradable polymers (e.g. BIOTEC™) is also produced by reaction–compounding process technologies to produce TPS™ derivatives and starch esters in a continuous extrusion process. The product BIOFLEX™ is used for garbage bags and shopping bags (Lorcks 1998).

Polylactic acid (PLA) is another aliphatic polyester that has potential for use in disposable and biodegradable plastic bags (Ke and Sun 2001). Blending starch with PLA increases biodegradability and reduces costs. However the brittleness of the starch/PLA blend is a major drawback for many plastic bag applications.

Novon International produces Novon, a starch-based resin that contains performance enhancing additives, such as synthetic linear polymers, plasticizers, and compounds that trigger or accelerate degradability. Novon is intending to mixed with synthetic polymers to create a plastic product, while making the product more degradable than traditional synthetic plastics (Biby 2002). A typical product would contain about 43% starch, 50% synthetic polymer, and 7% proprietary ingredients. Typical application is for agricultural mulch films and shopping bags. Current sole production capacity is in New Jersey (Biby 2002).

Since PLA is not well suited to flexible film production (other than substitutes for biaxially orientated PP and PS), PLA and starch blends (PLA-S) have been developed. Blending starch with PLA increases biodegradability, flexibility and reduces cost. The brittleness of PLA-S blends is the major drawback and this is overcome with the addition of plasticizers such as acetyl triethyl citrate (AC), triethyl citrate (TC), polyethylene glycol (PEG) and polypropylene glycol (PPG).

Ultimately most commercial biodegradable plastics for bags are either copolymers (to improve physical properties) or blends (to reduce cost).

### 2.1.3 Polysters

The majority of degradable polymer types outside of those based on polyethylene containing prodegradant additives are those that belong to the polyester family (e.g. polylactic acid (PLA); polycaprolactone (PCL); polybutylene succinate (PBS); poly(butylene succinate-co-adipate) (PBSA) copolymers; polylbutyrate adipate terephthalate (PBAT); aliphatic copolysters; modified PET (Biomax™); polyhydroxybutyrate (PHB) & polyhydroxybutyrate blended with poly-(3-hydroxy-butyrate-valerate) (PHB/V).

PHB and its copolymers with polyhydroxyvalerate (PHV) are melt-processable semi-crystalline thermoplastics made by biological fermentation from renewable carbohydrate feedstocks. They represent the first example of a true biodegradable thermoplastic produced via a biotechnology
A popular variant that is emerging for plastic bags is blends of PHB with PCL. The development of biodegradable plastic blends based on PHB and PCL which decompose completely into carbon dioxide (CO$_2$) and water (H$_2$O) by microorganisms was undertaken by Urakami (2000). The mechanical properties of PHB/PCL blend polymers were studied. The elongation in tension and the impact strength which were weak points of PHB and the elastic modulus which was a weak point of PCL were ameliorated by blending PCL into PHB in the range of 40 to 60%, and these mechanical properties were superior to those of PHB/PHV copolymers and LDPE. The impact strength and the heat stability increased when large percentages of PHB were blended into PCL and the PHB/PCL (60/40) blend polymer showed especially high impact strength and stability below 100°C (Urakami et al. 2000).

A particular group of polyesters are known as aliphatic-aromatic copolyesters (AAC) and these combine the biodegradability 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 a property profile similar to those of commodity polymers such as polyethylene.

Whilst being fossil fuel-based polymers, AAC degrade completely in soil or compost within a few weeks leaving no residue. The two main types of commercial AAC plastics are Ecoflex™ and Eastar Bio™ produced by BASF and Eastman respectively. 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. AAC come closer than any other biodegradable plastics to equaling the properties of low-density polyethylene, especially for blown film extrusion to produce plastic bags. To reduce cost, AAC is often blended with thermoplastic starch.

### 2.1.4 Controlled degradation master-batch additives

EPI has developed a series of Totally Degradable Plastic Additive (TDPA™) formulations that, when compounded with conventional polymers at appropriate levels, control the lifetimes of plastic films and articles. Stability is maintained during processing, storage and short-term end use. Once the material is discarded, oxidative degradation (initiated by heat, UV light or mechanical stress in the environment) is accelerated by as much as several orders of magnitude. The oxidized molecular fragments are hydrophilic, have molecular weight values reduced by a factor of ten or more, and are biodegradable.

Prodegradants in the EPI degradable plastics (and analogues by other manufacturers) include additives based on transition metal ions (Mn, Cu, Fe, Co, Ni, Ce$^4$) and metal complexes (e.g. cobalt stearate, cerium stearate), which render conventional polyethylene susceptible to

---

$^4$ Mn = manganese, Cu = copper, Fe = iron, Co = cobalt, Ni = nickel and Ce = cerium
hydroperoxidation. The critical point is that only trace quantities of Mn, Cu, Fe, Co, Ni and Ce are added to the polymer and these mirror the trace elements present in most soils.

These transition metal compounds are typically incorporated into the final formulation as additives at levels of a few percent. They are proprietary combinations of additives, which, with appropriate compositional adjustments, allow for a wide range of storage, use, and degradation times, depending on the end use and the environment. Polyolefin pellets which have been compounded with these additives are processed on conventional equipment at normal speeds. An important feature of these additives is that they are activated both by the action of sunlight and by heat.

This problem is that with so many different pro-degradant technologies the range of catalytic metals used is broad and testing for efficacy and residues becomes more complex. Also the degradability is dependant on the film/bag fabricator adding the correct level of master-batch. Quality assurance procedures need to be established to validate correct addition rates.

Indaco Manufacturing Ltd. in Toronto makes a recycled polyethylene-based bag known as Bio-Solo. The bags, which have been around since the early 1990s, use a non-starch formula and have an adjustable degradation time activated by heat and oxygen. The bag is marketed as compostable and degradable. Earthbound Systems Inc. in Moses Lake, Washington, has been distributing the Bio-Solo bags in the Pacific Northwest. Tests have shown that the bags have degraded in most systems from windrows to static piles and in most of the modern rapidly degrading composting systems of today (Biocycle, 2002).

2.1.5 Photodegradable polymers

‘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. Photosensitizers used include diketones, ferrocene derivatives (aminoalkyferrocene) and carbonyl-containing species. A new approach to making photodegradable plastics is adding metal salts to initiate the breakdown process. Many photodegradable polymers are a combination of PE and controlled degradation masterbatch additives (see section 2.1.4).

Evergreen Environmental, a South African company, has developed an additive system in conjunction with the University of Pretoria that causes plastic litter to degrade rapidly into water and carbon dioxide in the outdoors under the influence of the UV portion of sunlight and the action of oxygen in the air. By introducing a prodegradant into plastic bag production, the life of the plastic bag is reduced which would ultimately reduce the build-up of litter in the environment. The Wildlife and Environment Society of South Africa has also endorsed this technology.

PDQ additive and degradable masterbatches by Willow Ridge (Willow Ridge (Erlanger, Ky. USA) is a proprietary non-starch master-batch that simultaneously triggers photodegradation and thermal-oxidative breakdown in PE and PP. The product is typically used at a 3% level (Leaversuch 2002). This additive is offered for garbage bags and shopping bags. Willow Ridge also supplies a photodegradable master-batch designated UV-H that accelerates UV
degradation by creating free radicals that sever the polymer chains into smaller fragments that can be consumed by microbes. UV-H costs $1.50/lb and is typically used at a 2% level. It can be combined into a triple-acting system with PDQ, called PDQ-H (Leaversuch 2002). Willow Ridge’s additives are effective alone or in synergistic blends of additives that exploit different degradation mechanisms. Thermal-oxidative effects of PDQ, for instance, lower the onset temperature for degradation of disposed products and accelerate degradation activity (Leaversuch 2002).

2.1.6 Water soluble polymers

There are two types of water-soluble plastic commercially available - poly vinyl alcohol (PVOH) and ethylene vinyl alcohol (EVOH). The main water-soluble polymer used for bags is PVOH. New grades of PVOH have recently been commercialized, which incorporate an internal plasticizer and can therefore be extruded and retain their water solubility.

2.2 Degradation pathways of major types of degradable bags

2.2.1 Mechanism of degradation and biodegradation

Ideally, degradable plastics bags should undergo degradation pathways that ultimately lead to the bioconversion of the polymer into carbon dioxide (aerobic conditions) or carbon dioxide/methane (anaerobic conditions) and biomass (Biby 2002).

Degradation of 'true' biodegradable polymers to carbon dioxide and water will occur only when the polymer is exposed to microorganisms found naturally in soil, sewage, river bottoms and other similar environments. Other degradable polymers based on combinations of polyethylene and prodegradants do not require microorganisms (at least initially) but require activation by heat or light exposure.

Biodegradation is degradation of organic material, caused by biological activity - mainly microorganisms’ enzymatic action. This leads to a significant change of chemical structure of the material. The end-products are carbon dioxide and new biomass, and water (in the presence of oxygen) or methane (when oxygen is absent), as defined in the European Standard (prEN 13432 2000).

Four mechanisms are often involved in the environmental degradation of degradable polymers (Chapman 2001):

- The oxidation of the polyolefins or other polymers;
- The microbiological digestion of the natural ingredient, such as starch or cellulose;
- The microbiological digestion of the biodegradable polymer such as aliphatic polyesters; and
- The microbial digestion of the polymer fragments.

The breakdown of degradable polymers has been categorized into two important but separate parts (Chapman 2001):
• Disintegration, in which the plastic materials disintegrate and are no longer visible, but the polymer chain is not completely eliminated; and

• Mineralization, in which the polymer chains are metabolized (usually after the initial oxidation process) to carbon dioxide, water and biomass.

2.2.2 Thermoplastic starch products

Starch is a linear polymer (polysaccharide) 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. The glucosidic linkages between the sugar groups are susceptible to enzymatic attack leading to a reduction in chain length and the splitting off of sugar units (monosaccharides, disaccharides and oligosaccharides) that are readily utilized in biochemical pathways.

Manufacturers of starch – PE blends describe their products as photo-biodegradable. For example, Lloyd Brooks, supplier of Earthstrength bags, claim the following:

**Biodegradation**

Conventional plastics have molecular sizes of millions of molecular units. Only plastics with molecular sizes less than 5000 molecular units can be degraded by microorganisms. The bio-degradation technology employed by Earthstrength involves embedding treated starch compounds into the plastic material to initiate and accelerate bacteria of micro-organism growth. The micro-organisms attack the polymer structure by digesting the starch compounds, causing the polymer to weaken and disintegrate into smaller and smaller molecular units, which can then be consumed by the micro-organisms. The disintegrated polymer is further degraded by bacterial activities (aerobic and anaerobic) into the final products of methane gas, carbon dioxide and water.

**Photo-degradation**

Plastic components have active sites where photo-sensitive additives are added to enhance photo-degradation of the plastic when exposed to sunlight. Absorption of UV rays causes the active sites to become highly charged or ‘activated’ to form radicals, which weakens the polymer structures.

Oxidation of the activated sites further enhances the degradation of the polymer structures. The disintegrated polymer is further degraded by bacterial activities (aerobic and anaerobic) into the final natural elements of methane gas, carbon dioxide and water. (Lloyd Brooks undated).

2.2.3 Polyesters

Polyester-based degradable polymers biodegrade by a hydrolysis mechanism and are often referred to as hydro-biodegradable polyesters. This is thus quite different to the prodegradant polyethylene systems that are inert to hydrolysis but undergo oxidation (see below).
2.2.4 Controlled degradation masterbatch additives

Polyolefins are hydrophobic and thus inhibit the growth of microflora on them; polyesters on the other hand are hydrophilic and therefore encourage the growth of microflora.

It has been found, however, that the oxidation products of polyolefins are biodegradable. Such products have molecular weights that are significantly reduced, and they incorporate polar, oxygen-containing groups such as acid, alcohol and ketone. This is the basis for the term oxo-biodegradable polyolefins. Oxo-biodegradation then denotes a two-stage process involving, in sequence, oxidative degradation, which is normally abiotic in the first instance, followed by the biodegradation of the oxidation products.

Oxidative degradation proceeds by peroxidation followed by radial formation leading to chain scission (Figure 1). Oxygen and heat or mechanical stresses cause the polyethylene to preoxidate. Heat of UV light then result in degradation to free radicals.

**Figure 1: A simplified scheme that illustrates the degradation by peroxidation of PE.**

\[
\begin{align*}
O_2 & \\
\text{heat or} & \text{heat or} & \text{heat or} & \text{heat or} & \text{heat or} & \text{heat or} & \text{heat or} & \text{heat or} \\
\text{PE} & \Rightarrow HC\text{-}OOH & \Rightarrow HC\text{-}O\text{-} + & \text{OH} & \\
\text{mechanical} & \Rightarrow & \text{UV light} & \Rightarrow & \text{stress} & \\
\end{align*}
\]

In order to control both the lifetime of a degradable plastic during use as well as the rate of biodegradation in the environment, the use of pro-oxidants (prodegradants) used must be controlled by appropriate antioxidants. The ratio of the concentration of the pro-oxidant to the concentration of the antioxidant allows one to tailor the period before degradation. Since the most successful pro-oxidants currently in use are transition metal ions (e.g. Ni, Co, Cu) that catalyse the decomposition of hydroperoxides. All of these time periods can be controlled by altering the additive formulation to suit different applications and different disposal conditions in a variety of geographic locations.

Compost bags produced using EPI’s TDPA® technology were evaluated by Prof. Bernhard Raninger (Loeben University, Austria) using the municipal composting plant of Vienna Neustadt. Detailed results have been published but the overall results may be summarised as follows: The TDPA®-modified PE bags did not interfere with the biodegradation of the normal input to the plant – about 10,000 tons annually of mixed household and green garden waste. The TDPA®-modified PE bags underwent biodegradation during the composting operation. The resulting compost product, which contained particulate and partially biodegraded plastics, was premium quality material and passed all the usual ecotoxicity tests. These included seed germination, plant growth and organisms survival (daphnia, earthworms) tests carried out in accordance with DIN V 54900-3, ON S 2200 and ON S 2300 national standards.
Heat generated microbially in composting is the ‘trigger’ that causes oxidative degradation of the PE, and this happens relatively rapidly because of the prodegradant. Molecular weight decreases cause polymer embrittlement, mechanical stresses from windrow turning speed up PE film fragmentation, and polymer surface area increases. The microorganisms in the compost biodegrade the oxidised plastic at molar mass values at least as high as 40,000, more rapidly as $M_w$ values are reduced further. This is the two-stage process referred to earlier, and it seems to proceed at a rate comparable to that of naturally – occurring plant material.

It is evident that oxo-biodegradable plastics based on polyolefins contribute to the amount and nutritive value of the compost because much of the carbon from the plastic is in the form of intermediate oxidation products, humic material and cell biomass. This is in contrast to plastics, such as hydro-biodegradable polyesters that biodegrade at rates comparable to purified cellulose. At the end of the commercial composting process, all of the carbon from the latter has been converted to CO₂ so there is a contribution to greenhouse gas levels but not to the value of the compost.

### 2.2.5 Photodegradable polymers

Photodegradable plastics are made to become weak and brittle when exposed to sunlight for prolonged periods. Such plastics break apart when exposed to sunlight and forces of nature, such as wave action.

Photodegradable products can reduce the visibility of 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, shading, etc. Photodegradable plastics may have application in products with high litter potential (e.g. shopping bags that float i.e. specific gravity < 1) and in those that pose a threat to animal and marine life.

### 2.2.6 Water-soluble polymers

The main water-soluble polymer used for bags is PVOH. PVOH does not primarily biodegrade, but simply dissolves when subject to an environmental exposure. Depending on the formulation used, PVOH materials can be designed to dissolve at preset temperature ranges centering on, for example, 20°C, 55°C or 80°C. After about two to twenty minutes immersion at the designated temperature, the ‘depart’ polymer dissolves in water leaving a harmless, non-toxic aqueous solution of polyvinyl alcohol with a small amount of glycerol. Once this comes into contact with micro-organisms such as those found in water treatment plants, biodegradation to carbon dioxide and water is claimed to take place within about 30 days.

Literature from PVOH manufacturers such as Kuraray Co. Ltd. indicated that PVOH can be biodegraded by activated sludge treatment. In soil biodegradation of PVOH however is not discussed and may be very slow.
2.2.7 Overview of degradation pathways

Table 2 reviews the likely and known degradation routes of common degradable plastic types used for bags.

Table 2 Known and likely degradation routes of common degradable plastic materials used for bags

<table>
<thead>
<tr>
<th>Category</th>
<th>Composition</th>
<th>Degradation pathway</th>
<th>Suitable environments for degradation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biodegradable starch-based polymers</td>
<td>Starch-polyester (PCL, PLA, PBAT or AAC) blends</td>
<td>Hydrolysis by hydrolytic scission of the ester bonds in the chain backbone</td>
<td>Compostable, biodegradable and marine degradable. Suitable for degradation in controlled composting facilities, activated sludge (sewerage treatment). Also degrades in soil.</td>
</tr>
<tr>
<td>Biodegradable polyesters</td>
<td>Polylactic acid (PLA)</td>
<td>As above</td>
<td>As above apart from composting at &lt;60°C within time limit for Standard</td>
</tr>
<tr>
<td>Controlled degradation masterbatch additives</td>
<td>Polyethylene with a prodegradant additive</td>
<td>Two-stage process involving, in sequence, oxidative degradation, which is normally abiotic in the first instance, followed by the biodegradation of the oxidation products.</td>
<td>Insufficient data but appears to be slow to degrade in compost and landfill. Fragment into fine residue in open air.</td>
</tr>
</tbody>
</table>

2.3 Suitability of degradable polymers for bags

While degradable plastic bags are set to begin to ‘replace’ conventional plastic bags their fitness for purpose needs to be assessed.

This section will:

- Review the mechanical property requirements of degradable plastics. Regular polyethylene shopping bags are generally made from high molecular weight virgin resins with excellent puncture and tear resistance. It is important that local and imported degradable plastic bags meet the stringent mechanical property requirements so that they are fit for purpose.

- Examine shelf-life consideration for degradable plastic bags. Due to their very nature some types of degradable plastics can start to prematurely degrade during periods of hot storage as may occur in warehouses and shipping containers. This partial degradation may compromise the mechanical properties of the bags leading to premature failure by ripping. Hot/wet storage may also be problematic for hydrolyzable plastic bags.

- Explore the ability of local manufacturers to accommodate degradable plastics on conventional extrusion/film blowing machinery and bag converting lines since degradable plastic formulations are not yet a ‘drop-in’ substitute for conventional polyethylene plastic resins.
• Seek to find estimates of the lifetimes of different degradable plastics in various disposal environments.

2.3.1 Mechanical property requirements

While the potential list of degradable polymer types is extensive there are certain degradable plastic systems that are preferred for the manufacture of plastic bags on the basis of their favorable property profile. The material must perform in a similar way to conventional polymers, and must be capable of being processed on conventional film manufacturing equipment. It must also remain stable (i.e. not degrade) until it has reached the end of its useful life.

2.3.2 Shelf life

Due to their very nature some types of degradable plastics can start to prematurely degrade during periods of hot storage as may occur in warehouses and shipping containers. This partial degradation may compromise the mechanical properties of the bags leading to premature failure by ripping. Hot/wet storage in particular is potentially problematic for hydrolyzable plastic bags.

The realistic shelf life for Mater-Bi™ bags is 2 years whereas for the EPI bags it is only up to 6 months at below 28°C (Hall 2003). In fact, EPI literature states that the EPI bags must be stored below 28°C. The problem is that most warehouses in Australia in summer reach temperatures up to 35°C.

For directly degradable polyester-based bags the shelf life is normally satisfactory but PCL-based bags can melt during hot storage. Further the very rapidly mineralizing types can break down in a few days after being filled with active organic contents so their usefulness as compost bags is limited (Chapman 1999).

PVB plastic bags are stable when stored in air and are quite stable when stored even in humid conditions.

2.3.3 Processability in Australia

These polymers can be processed on most blown film extruders with very little difficulty. There is a need to watch temperature sensitivity due to starch content and additional hardware is required for most systems in the form of a hot air dryer (pre-dries the material) to avoid premature degradation (hydrolysis) and surface defects e.g. bubbles.

2.3.4 Estimated lifetimes in disposal environments

The time taken to degrade in different disposal environments is critical in reaching any conclusions about potential environmental impacts and benefits.

Table 3 summarizes the available knowledge (some of it supplied by manufacturers), on degradation times, although in some cases available research data is limited and it depends very much on the surface area of products and environmental conditions (e.g. climate).
### Table 3: Degradation times

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Land litter</th>
<th>Marine litter</th>
<th>Freshwater litter</th>
<th>Commercial anaerobic composting</th>
<th>Commercial aerobic composting</th>
<th>Home composting</th>
<th>Wet landfill</th>
<th>Dry landfill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polylactic acid (PLA)</td>
<td>Some weight loss or decrease in tensile strength and elongation after 1 year in soil (Hoshino et al 2002)(^5)</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Unknown</td>
<td>2 weeks – 1.5 months (Weber 2000). Certified compostable against ASTM 6400-99 (Cargill Dow undated)</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
<tr>
<td>Starch – polyester blends</td>
<td>8 weeks in soil (Lim 1999)(^5)</td>
<td>50% weight loss in 20 weeks in Queensland (McLure 1996) and 30 weeks in South Australia (Hall 2003)</td>
<td>10-20% weight loss in 20 weeks in Queensland (McLure 1996)</td>
<td>Unknown</td>
<td>1-2 months (Weber 2000)</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
<tr>
<td>Starch – polyethylene blends</td>
<td>Disintegrates into a powder in 200 hours under accelerated weathering tests (EAM)</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Less than 2 months if 40% starch additive used or 9-10 months if 15% (EAM brochure). Between 3-14</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
</tbody>
</table>

---

\(^5\) This probably overstates degradation in litter as many items do not get buried by soil.
Earthstrength bags start to physically disintegrate after 4 weeks of UV radiation (MPT 2003).

Earthstrength bags are degraded by microorganisms but extent of ultimate biodegradation is unknown (MPT 2003).

Polyethylene with prodegradant

<table>
<thead>
<tr>
<th>Duration</th>
<th>Disintegration</th>
<th>Biodegradation</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 weeks for disintegration (de Kleijn 2003)</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
<tr>
<td>Unknown</td>
<td>Unknown</td>
<td>Loss of mechanical properties in 11 days; 60% mineralization in 18 months. Product was tested after pre-oxidation(^6) (Chiellini et al/ 2003). Manufacturers claim 4-16 weeks (Foster 2003)</td>
</tr>
<tr>
<td>Unknown</td>
<td>Unknown</td>
<td>Disintegration 3-5 years, Biodegradation 5-10 years (EPI brochure)</td>
</tr>
</tbody>
</table>

\(^6\) The LDPE / TDPA film samples were submitted to a thermal-oxidative degradation treatment in order to mimic the thermophilic phase of a full-scale composting process (by heating in an oven at 55°C)
2.4 Short list of polymer options
While the potential list of degradable polymer types is extensive there are certain degradable plastic systems that are preferred for the manufacture of plastic bags on the basis of their favorable property profile.

The degradable plastic materials that are suitable for applications in film blowing for shopping bags and are/or currently available on the market that will be investigated in the current study are:

- Starch-polyester blends including:
  - Starch with polycaprolactone (PCL) (e.g., Mater-Bi™);
  - Starch with polybutylene adipate terephthalate (PBAT) (e.g., Ecoflex); and
  - Starch with polybutylene succinate/adipate (PBS/A) (e.g., Bionelle™).

- Starch -polyethylene blends (e.g. Earthstrength)

- Polyethylene + prodegradant (e.g. TDPA™)

- Polylactic acid (PLA).

2.5 Plastic bag use in Australia

2.5.1 Overview
It is estimated that over 10 billion bags are consumed in Australia each year\textsuperscript{7}. Most of these are retail shopping bags (6.9 billion), followed by produce bags (1 billion) and freezer bags. The estimated break down by product is provided in Table 4.

\textsuperscript{7} Estimates based on number of product units from \textit{Retail World Australasian Grocery Guide} 2003 and personal communication with a range of companies
Table 4 Total bag use in Australia per year (Reid 2003)

<table>
<thead>
<tr>
<th>Type of bag</th>
<th>Total consumed units/ per annum</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDPE shopping bags</td>
<td>6 billion</td>
</tr>
<tr>
<td>LDPE shopping bags</td>
<td>900 million</td>
</tr>
<tr>
<td>Bait bags</td>
<td>11 million</td>
</tr>
<tr>
<td>Garden bags</td>
<td>19 million</td>
</tr>
<tr>
<td>Garbage bags</td>
<td>250 million</td>
</tr>
<tr>
<td>Kitchen tidy</td>
<td>330 million</td>
</tr>
<tr>
<td>Produce bags</td>
<td>1 billion</td>
</tr>
<tr>
<td>Sandwich and storage</td>
<td>830 million</td>
</tr>
<tr>
<td>Bread bags</td>
<td>365 million</td>
</tr>
<tr>
<td>Ice bags</td>
<td>Unknown</td>
</tr>
<tr>
<td>Freezer bags</td>
<td>720 million</td>
</tr>
</tbody>
</table>

2.5.2 Shopping bags

Local manufacturers and wholesalers

Local manufacturers of bags in Australia are:

- Plaspak Pty Ltd
- Maxpak Pty Ltd
- Detmark Pty Ltd
- Valpak Pty Ltd.

Plastic bags are sold by manufacturers to wholesalers. There wholesalers sell both local and imported bags. Table 5 shows estimates of the number of wholesalers operating in each state. Some companies are small, family run business. When interviewed some did not know about degradable bags.
### Table 5 Number of bag wholesalers in each state (Yellow Pages Online, 2003)

<table>
<thead>
<tr>
<th>State</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Victoria</td>
<td>105</td>
</tr>
<tr>
<td>Australian Capital Territory</td>
<td>7</td>
</tr>
<tr>
<td>New South Wales</td>
<td>93</td>
</tr>
<tr>
<td>Northern Territory</td>
<td>2</td>
</tr>
<tr>
<td>Queensland</td>
<td>70</td>
</tr>
<tr>
<td>Queensland</td>
<td>7</td>
</tr>
<tr>
<td>Tasmania</td>
<td>20</td>
</tr>
<tr>
<td>Western Australia</td>
<td>28</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>332</strong></td>
</tr>
</tbody>
</table>

### Types of bags

The major plastic bag types used in Australia are the ‘singlet’ bag, made of high-density polyethylene (HDPE) and the ‘boutique’ style bag, made of low density polyethylene (LDPE). Some HDPE bags are also used in a ‘wave top’ shape, with a reinforced handle.

The HDPE singlet bag is generally used in supermarket bags, fresh produce bags, take-away food bags and other non-branded applications. The LDPE boutique and HDPE wave top bags are generally branded and used to carry higher value goods such as clothing.

Industry data indicates that 6.9 billion, or over 36,000 tonnes, of plastic shopping bags were used in Australia in 2001.

### Costs

The ‘free of charge’ nature of shopping bags is longstanding and consistent with all other forms of packaging in Australia. Plastic shopping bags cost the retailer around three cents each on average, but range in cost from 1 cent to 12 cents per bag depending on weight and volume. This is generally built into the product cost and represents much less than 1% of the total transaction cost. Supermarkets bags generally cost the retailer 1.5 – 2 cents each. It is estimated that the annual average cost per household for plastic shopping bags is likely to be $10-15 per year. Some European owned stores currently operating in Australia, (such as Aldi and IKEA) have introduced charges for bags. Bunnings recently announced that it will also be introducing a charge for point of sale bags.

Many of the plastic bags utilised by Australian retailers are imported. It is estimated that 67% of HDPE singlet bags are imported, with approximately 4 billion units of HDPE bags imported in 2001/2002 with the remaining 33%, or 2 billion units, produced in Australia. A small portion of bags are made with recycled content. This is set to increase with recent commitments from major supermarkets to utilise recycled content in a proportion of their bags. This recycled content is currently mostly from industrial waste sources. The recent commitment from retailers...
will see an expansion of recyclate from shopping bags being used in bag manufacture. This has already commenced with recycled content bags produced by Detmark being used in IGA stores in regional Victoria. 225 million (or 25%) of LDPE bags were imported in 2001/02, with 675 million (or 75%) produced in Australia.

**Destination**

There is a high level of single reuse of plastic shopping bags, with an estimated 60% of householders reusing bags. Recycling levels are currently low (3% of bags or 5% of supermarket bags). This is in part due to this reuse, inadequacy or inconvenience of current recycling systems and a low consumer awareness of collection services. During the focus group (section 3.2.2), participants expressed mistrust of current recycling systems and also commented that they often forgot to bring their bags to the supermarket for recycling. The current disposal routes and destinations are outlined below.

**Reuse**

Due to their inherent usefulness in carrying and containing objects, many plastic shopping bags are used beyond their ‘single use’ life. Clean Up Australia recently conducted a survey of bag reuse and recycling (Clean Up Australia 2002). Despite a small sample number, the results were in line with other surveys conducted by other organisations, i.e.:

- 15.6% of bags are reused
- 13.2% of bags are reused as bin liners
- 13.9% of bags are recycled

Other surveys carried out include a survey carried out by the Plastics Industries Association (1992) which indicated that 85% of people reused plastic shopping bags for some application, and a more recent survey carried out by Quantum (2002) found that 75% of people reused shopping bags as bin liners or waste bags, with other reuses on top of this again.

**Recycling**

Drop-off bins are provided at many major supermarkets for used bags, which are collected for recycling. This is collected in conjunction with the back of store collection of post industrial scrap such as shrink wrap (Pym 2003). The current in-store drop-off recycling system is for HDPE shopping bags only.

It is estimated that in 2001/02, 1,000 tonnes of bags, or approximately 180 million units, were recycled in this manner, with the majority exported for reprocessing. This represents a recycling rate of approximately 3% of retail shopping bags. About 50 tonnes was reprocessed in Australia, with the reprocessed material utilised in pipe manufacture.

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8 A more conservative estimate of 60% was used for the LCA in this study.
Recycling of plastic shopping bags via the kerbside recycling system is limited to a few council areas in South Australia, New South Wales and Victoria. In all other areas, any plastic bags placed in the kerbside recycling stream are not sorted and are disposed to landfill.

**Disposal**

Currently, the vast majority of waste produced in Australia is disposed to landfill. Some plastic shopping bags are disposed directly into the waste stream, while many are reused as garbage bags, and are subsequently disposed to landfill.

Very little waste currently disposed of in Australia undergoes alternative waste treatment such as waste to energy. It is therefore assumed that all plastic shopping bags are eventually disposed to landfill aside from those recycled and those not recovered from the litter stream. Annual plastic bag disposal to landfill is therefore estimated at 6.67 billion units or approximately 36 700 tonnes per year.

**Littering**

Of the 6 billion HDPE bags and 0.9 billion LDPE bags distributed annually in Australia, a certain percentage are littered, either directly by consumers or from being blown out of the garbage stream and landfills, however the actual number of bags currently in the environment and the number littered annually is not known.

Litter collection data from Clean Up Australia (2002) indicates that plastic bags make up 2.02% of the litter stream. Keep Australia Beautiful (Victoria) data (1999) indicates that all plastic items make up an average of 26.7% of the litter stream by item, which includes items at landfill sites where plastic items make up 47% of the total. It is estimated by Keep Australia Beautiful that ‘bags, sacks and sheeting’ makes up an average of 6.2% of the litter stream by item in Victoria; however the shopping bag breakdown of this is not known, and as surveys were carried out in rural sites along with metropolitan sites, this is believed to consist of significant numbers of items such as silage wrap and sacks etc. However, assuming approximately one third of this percentage is plastic shopping bags, the data would appear to correlate with the Clean Up Australia data of approximately 2% of the litter stream.

As there is no data available on the total size of the litter stream in Australia, this data cannot be applied to determine the total number of bags entering the litter stream. In this report, it has been estimated that a total of between 50 and 80 million bags enter the environment as litter annually. This equates to approximately 20% or less of the bags utilised in outdoor away-from home locations being littered, with a further one third of the total litter stream coming from inadvertent litter sources through waste management activities, as data on the litter occurrence around landfills would infer. It is assumed that the vast majority of these bags would be HDPE bags. The existing data on litter would need to be improved in order for performance related targets to be reliably measured.

Approximately $200 million dollars are spent annually by local and state governments on total litter clean ups (Nolan-ITU et al 2002: 8). In addition private sector companies such as landfill operators and community organisations, such as Clean Up Australia, also devote considerable
resources to litter recovery. As plastic shopping bags are a highly visible litter object, it is probably fair to allocate more than 2% of litter clean-up costs to bag clean-up costs. Therefore a figure of approximately $4 million is deemed attributable to shopping bags.

2.5.3 Overview of total bag use

Table 6 provides a summary of total bag use, litter impacts, potential for recycled content\(^9\) and recycling, and the main Australian suppliers.

Table 6 Total bag use, risk of litter, potential for recycled content and recycling, and suppliers

<table>
<thead>
<tr>
<th>Bag Type</th>
<th>Number</th>
<th>Tonnes of plastic (Reid 2003)</th>
<th>Level of litter</th>
<th>Potential for recycled content</th>
<th>Potential for recycling programs</th>
<th>Current suppliers of degradable bags</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDPE Shopping bag</td>
<td>6 billion</td>
<td>36 000</td>
<td>Significant</td>
<td>High</td>
<td>High</td>
<td>ValPak/ Jonmar/ Detmark/ Plaspak/ Bagsplus</td>
</tr>
<tr>
<td>LDPE Shopping bag</td>
<td>900 million</td>
<td>16 000</td>
<td>Significant</td>
<td>High</td>
<td>High</td>
<td>As above</td>
</tr>
<tr>
<td>Bait Bags</td>
<td>11 million</td>
<td></td>
<td>Significant</td>
<td>Low</td>
<td>Low</td>
<td>Jonmar</td>
</tr>
<tr>
<td>Green waste/ Compost bags</td>
<td>19 million</td>
<td>204</td>
<td>Insignificant</td>
<td>Med</td>
<td>Low</td>
<td>Jonmar</td>
</tr>
<tr>
<td>Bread Bags</td>
<td>365 million</td>
<td>20 000</td>
<td>Significant</td>
<td>Low</td>
<td>Medium</td>
<td>Earthstrength (Lloyd Brooks)</td>
</tr>
<tr>
<td>Ice bags</td>
<td>Unknown</td>
<td>200</td>
<td>Significant</td>
<td>Low</td>
<td>Low</td>
<td>Jonmar</td>
</tr>
<tr>
<td>Freezer bags</td>
<td>700 million</td>
<td>1 600</td>
<td>Insignificant</td>
<td>Low</td>
<td>Low</td>
<td>Earthstrength</td>
</tr>
<tr>
<td>Garbage bags</td>
<td>250 million</td>
<td>800</td>
<td>Insignificant</td>
<td>High</td>
<td>Low</td>
<td>Jonmar</td>
</tr>
<tr>
<td>Kitchen tidy bags</td>
<td>330 million</td>
<td>1 800</td>
<td>Insignificant</td>
<td>Low</td>
<td>Low</td>
<td>Jonmar/ Earthstrength</td>
</tr>
<tr>
<td>Sandwich/ Storage bags</td>
<td>800 million</td>
<td>2 000</td>
<td>Significant</td>
<td>Low</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>Produce bags</td>
<td>1 billion</td>
<td>2 500</td>
<td>Insignificant</td>
<td>Low</td>
<td>Med</td>
<td></td>
</tr>
</tbody>
</table>

\(^9\) An Australian Standards strictly controls plastics in food contact. Manufacturers in Australia seek a ‘letter of no objection’ from the Food and Drug Administration (FDA) in the US for recycled plastics in food contact. This is difficult to achieve. The aim is to ensure that the plastic does not contain any contaminants that could migrate into the food product. Recycled PET is the only food contact recycled material in Australia with such approval.
**Bait Bags**

Bait bags are generally clear bags with a light gauge. Bait bags are usually sold to the bait manufacturer where they are filled and then sold to the consumer. The potential for recycled content is low. Due to the high level of contamination the potential to add bait bags to a recycling program is also low and there is currently no reuse of bait bags. Bait bags are used for fishing and are often consumed away from waste disposal systems. There are reports of the littering of bait bags in the marine environment (Clean Up Australia 2002).

**Green waste/compost bags**

Garden bags are consumed in low volumes but with a heavy gauge. It is likely that there is recycled content in many of the existing bags and there is a scope for more due to the green/black colour of the bag. There is no formal recycling program in place to capture these bags. While there is some manufacturing of plastic bags in Australia many are imported from China, Malaysia or Indonesia. There is some reuse of the bags if the leaves are transferred from the bag to an alternative container for disposal, either a compost bin or green waste bin. There is a problem with green waste bags ending up at organic processing facilities and contaminating the end compost.

**Bread bags**

A significant volume of bread bags is consumed each year. The bags are a clear, light gauge and have a high print content. There is little presence of bread bags in the litter waste stream. There is limited scope for recycled content due to the contact of the plastic film on the bread and the requirement for the bag to be clear. There is a potential for a recycling scheme to be put in place to capture these bags. They end up in the home and may be reused, e.g. as lunch bags. They are disposed through the household garbage waste stream.

**Ice bags**

Ice bags are made from large, heavy gauge bags. The requirement for clear colour makes recycled content unlikely. Ice in bags tends to be sold at petrol stations and there is a low volume of use. A significant portion is used away from home with some found in the litter stream. There is no current reuse of ice bags and a low potential for them to be included in the recycling stream.

**Freezer Bags**

Over 700 million freezer bags are sold each year. They are a light gauge and small in size therefore use small quantities of plastic. They tend to be clear in colour and because they come into contact with food, recycled content is unlikely. Due to high contamination from food there is little potential for freezer bags to be included in a recycling program. They are consumed almost entirely in households and they are unlikely to be found in the litter stream. The majority of freezer bags are imported from China and Indonesia.
Garbage bags

It is estimated that 250 million bags garbage bags are used each year. The market is shared evenly between import and local manufactured bags with the imports coming from Thailand and Indonesia. Both local and imported bags are likely to include recycled resin. Most bags are collected with domestic garbage waste stream so recycling of the bags is not feasible. There is some littering from dumping of bag with their contents.

Kitchen tidy bags

It is estimated that 330 million bags are used per annum. There is some manufacturing in Australia but the majority are imported from China or Thailand. They use thin gauge film. Almost all are used at home and it is unlikely that they will be found in the litter stream. There is potential for them to contain recycled content but because they contain waste when disposed there is a low potential for them to be included in a recycling program.

Sandwich/ storage bags

Over 800 million sandwich bags are used each year. They are very small and have a light gauge therefore use a small volume of plastic. Some will end up in away from home destinations. Almost all are imported from China and Thailand. Due to their contact with food and the need for a clear film there is a low potential for them to contain recycled content. There is potential for them to be included in a recycling program.

Produce Bags

Over 1 billion bags are used each year. They are a light gauge and small size. Their opaque colour and their contact with food make the use of recycled content unlikely. There is potential for them to be included in a recycling program. They are consumed almost entirely in households with a small number found in the litter stream.
3 Current and proposed use of degradable bags in Australia

This section provides an overview of:

- Current and proposed use of degradable bags in Australia; and
- Consumer attitudes to degradable bags.

3.1 Current and proposed applications in Australia

There are two types of degradable bags available in Australia. Biodegradable starch based bags and additive masterbatch prodegradant bags. There is only one manufacturer of starch-based bags – Jonmar - with the remaining bags being imported from overseas.

Other bag manufacturers are using prodegradant additives with PE. EPI is current selling TDPA additive masterbatches, (a prodegradant) to a number of Australian companies to be used in plastic bag manufacturing. Companies currently using this technology include:

- Plaspak Pty Ltd.
- Maxpak Pty Ltd.
- Detmark Pty Ltd.
- Valpak Pty Ltd.

There are a number of manufactures and wholesalers who are on-selling TDPA additive masterbatch based plastic bags into Australia. The degradability relies on the addition rates of the masterbatch. This may be highly variable from one processor to the next hence the degradation rates are highly variable.

Several companies are trying to introduce bags made from starch – PE blends. These companies include Lloyd Brooks, who is importing bags from Malaysia under the Earthstrength brand. Their bags are already used for bread bags (Tasmania) and organics bags (a kerbside trial in Port Macquarie) but they hope to introduce a degradable shopping bag to the market.

Other companies marketing starch – PE blends include MEBI (manufactured in China) and EAM (manufactured in India).

Table 7 provides a list of the current applications for degradable shopping plastic bags, and Table 8 for other bag applications. Information was sourced from industry interviews10.

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10 Alan Reid, Valpak; John Ferman, Jonmar; Malcolm Davidson, Detmark Polybags; John Ryalls, Maxpak; Ray Watkins, Earthstrength; Warwick Hall, Plastral Fidene Pty Ltd
Table 7: Current use of degradable polymers in shopping bags

<table>
<thead>
<tr>
<th>Product</th>
<th>Current Purchasers</th>
<th>Supplier</th>
<th>Type of degradable polymer</th>
<th>Shopping bag costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shopping bags</td>
<td>Butchers/ chemist shops/ Deli</td>
<td>ValPak (Amcor film)</td>
<td>PE / prodegradant</td>
<td>1.6 – 2.9</td>
</tr>
<tr>
<td>Shopping bags/ show bags/ ice bags</td>
<td>Queensland Government/ Shopbasics</td>
<td>Jonmar</td>
<td>Corn Starch</td>
<td>17-22</td>
</tr>
<tr>
<td>Shopping bags</td>
<td>Export overseas for use in small supermarkets</td>
<td>Detmark</td>
<td>PE / prodegradant</td>
<td>1.7-2.5</td>
</tr>
<tr>
<td>Shopping bags</td>
<td>EarthBasics (Wholesalers of plastic bags)</td>
<td>Jonmar</td>
<td>Corn Starch</td>
<td>17-22</td>
</tr>
<tr>
<td>Shopping bags</td>
<td>Sims Supermarkets</td>
<td>Plaspak</td>
<td>PE / prodegradant</td>
<td>2</td>
</tr>
<tr>
<td>Shopping bags</td>
<td>Ritchies Supermarkets</td>
<td>Maxpak</td>
<td>PE / prodegradant</td>
<td></td>
</tr>
<tr>
<td>Shopping bags</td>
<td>Small Supermarkets</td>
<td>BagsPlus (import bags from Singapore)</td>
<td>Unknown</td>
<td></td>
</tr>
<tr>
<td>Shopping bags</td>
<td>Clothing Boutiques</td>
<td>Gispac Pty Ltd (import bags)</td>
<td>PE / prodegradant</td>
<td>30% more expensive than normal</td>
</tr>
<tr>
<td>Shopping bags</td>
<td>Wholesalers of plastic bags</td>
<td>Marinucci Packaging</td>
<td>PE / prodegradant</td>
<td>1.8</td>
</tr>
</tbody>
</table>
### Table 8 Current use of degradable polymers in other bags

<table>
<thead>
<tr>
<th>Product</th>
<th>Current Purchasers</th>
<th>Supplier</th>
<th>Type of degradable polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bait Bags</td>
<td>Markwell’s Bait</td>
<td>Jonmar</td>
<td>Corn Starch</td>
</tr>
<tr>
<td>Dog waste bags</td>
<td>Brisbane City Council</td>
<td>Jonmar</td>
<td>Corn Starch</td>
</tr>
<tr>
<td>Car bags (part of the “Keep Our</td>
<td>Holroyd City/ Auburn Council/ Fairfield City/ Parramatta</td>
<td>Jonmar</td>
<td>Corn Starch</td>
</tr>
<tr>
<td>Cities Beautiful Campaign”)</td>
<td>City Council</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Show bags/ Ice bags</td>
<td>Queensland Government/ Shopbasics</td>
<td>Jonmar</td>
<td>Corn Starch</td>
</tr>
<tr>
<td>Household bags (organics kerbside</td>
<td>Port Macquaire City Council</td>
<td>EarthStrength</td>
<td>Tapioca Starch</td>
</tr>
<tr>
<td>collection trial)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bread bags</td>
<td>Local bakery, Coles Bay, Tasmania</td>
<td>EarthStrength</td>
<td>Tapioca Starch</td>
</tr>
</tbody>
</table>

In addition to the TDPA additive masterbatch other similar prodegradant technologies from overseas are now being evaluated in Australia such as:

- Totally Degradable Plastic™ from Symphony Environmental (UK)
- Addiflex™ from Sekundanten AB in Sweden
- Degrade™ bags from Evergreen Environmental in South Africa*
- PDQ additive and degradable masterbatches (Willow Ridge)
- Bio-Solo from Indaco Manufacturing Ltd. (Toronto)

Joint Services Australia is currently trying to enter the market with degradable bags (imported from Malaysia) including food freezer bags, refuse sacks and shopping bags. These are not on the market currently.

Cost is a major barrier to increased use of degradable bags for shopping bags. HDPE/ LDPE retail carry bags cost approximately 1.3 cents per bag. Manufacturers confirmed that biodegradable plastic retail carry bags range from 1.6 cents to 22 cents. They anticipate that within 3-5 years the cost of biodegradable bags will be similar to HDPE/ LDPE plastic bags.

Filmwrap and bags for food scraps, food residuals and food products destined for composting in commercial composting facilities, are potential application areas 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 potential applications depend on the disposal environment being a commercial composting operation, which provides the necessary conditions for the polymers to degrade.
Nillumbick Shire Council is currently introducing a new waste collection system, which includes the collection of food waste in the green waste stream (Steel 2003). Other councils, including Port Macquarie City Council, are currently investigating this waste collection system. 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 tonnes per annum production plant servicing this market. Such bags would take 8-10 weeks to fully degrade in a commercial composting operation.

3.2 Consumer research

3.2.1 Ritchies Supermarkets

Ritchies Supermarkets use a degradable shopping bag with a prodegradant additive, and claim that feedback from customers has been very positive. The bags include the following messages “100% degradable plastic bags”, “This bag will degrade in a landfill site leaving no harmful residues” and “Please do not litter”. Feedback from customers is that the bags have encouraged more responsible consumer behaviour in other areas (Craven 2003).

3.2.2 Consumer focus group

A market research focus group, with ten randomly selected participants, was conducted to as part of this project to ascertain consumer’s views about degradable plastic bags. The study started by discussing shopping habits of consumers and then moved into product packaging and the effect that packaging had on consumers’ choice in products. The final stage of the focus group looked at the use of plastic bags when shopping and the introduction of degradable bags into the supermarket.

Shopping habits

Participants were asked to describe how often they shopped, when they shopped and how many products they bought in each shopping trip. While two participants still did one shop a week the majority of participants did a number of small shops a week, sometimes as often as once a day. These shoppers did not plan out their shopping and only bought enough products to meet their immediate needs. This was due to time and family pressures and the convenience of 24 hour shopping.

Shopping often occurred on the way home from work with consumer purchasing approximately eight items at a time. If the consumer was going to the local supermarket they would walk but the majority of shopping was taken home in the car. Some participants did part or all their shopping at a market but this was not on a regular basis.
**Packaging and the environment**

The thought process that participants used when choosing a product varied between participants and sometimes for each individual shopping trip. A greater emphasis was placed on the cost of a product followed by convenience and health. The environmental impact of the packaging was of some consideration and several participants commented that often they found that by choosing a product with minimum packaging it also had a reduced cost.

When cost was not a consideration then they would place a greater emphasis on an environmentally preferable product. If there was strong advertising for an environmentally friendly product they would choose this product but would not select the product based on the environmental benefits of the packaging. Participants said they would not specifically look for the recyclability of a product but would notice the recycling symbols if they were prominent. They also considered a product that had “degradable” on the packaging as an environmentally wise choice.

**Shopping bags**

All of the participants commented that they, as individuals, and society as a whole, used too many shopping bags. The majority of the group owned calico bags for shopping but did not bring them on each shopping trip. The unplanned nature of shopping made it harder to remember to bring the bags all of the time. Plastic bags were seen as a method that stores used to enforce security and prevent shoplifting. They also valued the role of shopping bags in protecting their privacy when they left the store after purchase.

All participants reused shopping bags for activities such as rubbish bags, school fetes, nappy bags and lunch bags. The reuse of bags at the supermarket was influenced by the attitude of the cashier at the supermarket. The majority of the group had encountered resistance to the use of their own reusable bags, e.g. feeling that the cashier didn’t want to use them. The cashier was seen as having a large influence over the number of bags that were used in each shop. It was suggested that cashiers should have an incentive scheme to reduce the number of bags they use. All participants wanted to be financially rewarded for reusing plastic bags or using an alternative to plastic bags.

**Degradable shopping bags**

All participants had heard about degradable bags. They were uncertain about how long it would take for them to degrade in the environment and were concerned that they would be unable to reuse them in the same way as normal plastic bags because they would degrade. They felt the greatest benefit of degradable bags was from their ‘reduced time in the environment’ and that for the bags to have a benefit they would have to degrade within a year. No negative impacts were perceived, although it was felt that they would result in an increase in bin liner use.

The participants felt that degradable bags would have the most benefit for animals and waterways. It was felt that the use of degradable bags would not result in an increase in litter.
Comments were made that people who litter do not consider the consequences of their litter, and the material used to make a product would have no positive or negative impact on this.

Many of the participants did not want the added pressure of choosing bag type in the supermarket. They wanted the decision made for them by the government or supermarkets.

There was some skepticism about the current recycling of plastic bags. Participants were not convinced that recycling companies were fulfilling their obligation to recycle the material that was given to them and would choose a degradable product to be guaranteed that they are ‘doing the right thing by the environment’. Participants that currently reused their plastic bags for bin liners etc would only agree to the degradable bags if they were still able to reuse them.

It was generally felt that the use of degradable bags was the solution to the overuse of plastic bags. There was concern however about the cost being potentially higher - it was felt that the government should subsidize the cost of the bags to make them either the same as or less than the price of conventional bags because of their perceived environmental benefits.

### 3.3 Possible impacts on the Australian manufacturers and wholesalers market

For the purpose of this report, plastic bags were defined as supermarket and retail shopping bags, green waste / compost bags, bin liners, fruit bags / mesh, bait bags, dog faeces collection bags, bread and ice bags; with the main focus on shopping carry bags.

Approximately 10.5 billion plastic bags are consumed in Australia each year. Most of these are retail carry bags (6.9 billion), of which around 60% are imported.

Companies that are likely to be affected by the introduction of degradable bags into the Australian include polymer suppliers and bag manufacturers. Some of the bag manufacturers already manufacture degradable bags using prodegradant additives, and all would have potential to supply degradable bags to meet market demand if required. Degradable polymers can be processed on conventional film blowing lines with only minor modifications.

There are a range of different degradable polymer bags already on the market in Australia, including:

- Oxo-biodegradable shopping bags, garbage bags and kitchen tidy bags (polyethylene and a prodegradant additive); and
- Biodegradable garbage bags, kitchen tidy bags, bait bags and dog faeces bags (starch – polyester or starch – polyethylene blends).

The oxo-biodegradable bags (polyethylene with prodegradant additives) and some biodegradable bags are manufactured in Australia, while others are imported. While current use of degradable bags is relatively small, many new film and bags applications are emerging in Australia. Any growth in demand for prodegradant bags could be met by existing Australian bag manufacturers with very little impact on resin suppliers (the additives are normally added at a rate of around 3%).
While there is one local manufacturer of starch-based polymer bags, Earthstrength tapioca starch bags are also imported from Malaysia, and some of the Mater-Bi bags are imported from Italy. While Australia has a strong agricultural sector that could potentially supply tapioca, corn or other crops for the manufacture of starch, the likelihood of a new polymer manufacturing industry being established in Australia is low. The Australian polymer industry has been undergoing a process of rationalization and down-sizing for many years in the face of heavy competition from lower cost suppliers overseas.
4 Degradable Bag Use in Europe

Chris Foster, a consultant in Europe, has provided an overview of markets and attitudes to degradable bags in Europe (Foster 2003).

4.1 Overall scale
Biodegradable plastic bags are currently available in Europe for the four main applications listed below.

- Supermarket carrier bags
- “Knot” bags (small bags used in supermarkets for fruit and vegetables)
- Kitchen waste bags
- Garden waste sacks

Total sales by producers in all of these areas remain small. Although numerous businesses can be found that make and/or distribute biodegradable plastic bags in European countries, most are small businesses or recent start-ups. A fair impression of the limited level of penetration that any of these products has achieved can be gained by looking into material use.

Data from the Association of Plastic Manufacturers in Europe (APME) suggest that total European polymer consumption for plastic bags and sacks is of the order of 2.0-2.5M tonnes per year (1999 data). This can be contrasted with the fact that total consumption of all biodegradable polymer products in the European Union in 2001 was estimated by IBAW (Interessengemeinschaft Biologisch Abbaubare Werkstoffe – the International Biodegradable Polymers Association and Working Groups) at 25,000 to 30,000 tonnes.

Consumption in 2003 of Novamont’s “Mater-Bi™” corn starch-derived material for plastic bags is apparently expected to be in the region of 8000 tonnes. This is, though, reported by IBAW to be the market leading biodegradable polymer for film and bags.

CargillDow’s “Natureworks™” polylactic acid (PLA) material is produced in larger volumes (global production capacity - none of which is in Europe - is understood to be almost 150000 tonnes), but this material is targeted mainly at rigid packaging and fibre applications, notably those where PET might otherwise be used. Another prominent player, using degradable polyethylene, indicated that their consumption of resin is “hundreds rather than thousands” of tonnes. Production of a number of other materials, such as BASF’s “Ecoflex™” polyester, is understood to remain on a pilot-plant scale at this time.

All participants in the market agree that it is growing.

4.2 Legal context
The first of these seeks to encourage recycling and recovery of packaging, setting targets for each, which every nation-state must achieve. Different nation-states have different mechanisms in place to achieve the targets. In all cases there is some transfer of funds to reprocessors to encourage recycling and recovery operations. For example in Germany and France retailers and consumers pay direct levies, while in the UK funds are collected from industry in a more complicated manner. The important points to note in relation to biodegradable plastic bags are that:

• They are not exempted from levies of this kind, and
• Composting is regarded as “recovery” rather than “recycling” for the purposes of the Packaging Directive – and it is the recycling targets that are the higher and more difficult to achieve.

The Landfill Directive, on the other hand, sets out to reduce the amount of waste being consigned directly to landfill. Pre-treatment of all wastes will eventually be required and in particular, biodegradable municipal waste going to landfills must be reduced to 35% of the total amount (by weight) of biodegradable municipal waste produced in 1995. There is therefore great interest throughout Europe in increasing the amount of biodegradable waste that is composted. The absolute scale of the challenge varies from country to country, of course, reflecting the varying dependence on landfill.

The Landfill Directive also imposes strict controls on the operation of landfills, with the result that smaller sites are expected to be less profitable in future. The number of landfills available to take waste is therefore falling across the continent (see Figure 2, following page).

So in summary we can identify the following forces:

• Pressure on landfill disposal
• Pressure to maximise use of existing landfill space
• Pressure to find ways of increasing the amount of biodegradable waste being composted, leading to growth of separate collection of various waste fractions
• No fiscal incentive for a switch from “conventional” polymers in packaging to biodegradable ones.

4.3 National patterns
Consumption of biodegradable plastic bags varies considerably from country to country around Europe.

The UK seems to have seen the highest uptake of degradable supermarket carrier bags, almost all made from polyethylene (PE) film containing a small percentage (less than 5%) of an additive that catalyses oxidative or photochemical degradation of the polymer.

The Co-Op (a retail and services group with a strong ethical and environmental profile) and Somerfield (a small-medium supermarket chain) are the best-known firms to have taken these bags on. They have received some endorsements from environmental groups, with the Soil
Association (a group supporting organic agriculture) issuing a press release commending Somerfield’s move, while the Royal Society for the Protection of Birds (RSPB) is about to begin using modified PE film from the same supplier for magazine wrapping, having satisfied itself that its use is not contradictory to RSPB’s conservation aims.

One clear advantage that this modified PE material has over other biodegradable polymers for this application is price – a key factor for any business seeking to supply supermarkets. Symphony Plastics, the leading converter of this material in the UK, indicates that the film is no more than 5-10% more expensive than conventional PE on a weight for weight basis, and that cost equivalence to carrier bags in conventional PE can be achieved if downgauging opportunities are seized. In contrast, processors of other biodegradable polymers indicated that carrier bags in their preferred materials would be anything from 1.5 to 6 times the price of those made from conventional PE. Notwithstanding the endorsements mentioned, there is considerable disagreement about the environmental benefits associated with the degradable polyethylene material.

Refuse sacks made from this degradable PE are also being sold with considerable success in Ireland – largely to public and commercial organisations with environmental policies. It is notable that these two countries are particularly dependent on landfill disposal as the waste management route of choice, and that in these circumstances a degradable material offers potential benefits.

Elsewhere in Europe, most sales of biodegradable plastic bags are as containers for organic wastes destined for composting. Several of the producers interviewed for this report said that this application is the main focus of their sales effort, and we can find no evidence that large German retailers, for example, have followed the example of Co-Op and Somerfield in the UK. Demand for biodegradable sacks and kitchen waste bags is reported to be growing everywhere, driven by the spread of separate collection schemes for biodegradable wastes and the promotion of home composting. Starch-based materials are the most popular for these bags, despite costs per bag some 3-5 times those for polyethylene. Buyers of sacks for organic refuse in particular may be less price-sensitive than supermarkets: they are either green-minded consumers or local authorities, which can pass the cost on to residents in aggregated waste collection charges. Starch-derived biodegradable polymers may be making inroads into the carrier bag niche – in July 2003 UK retailer Sainsbury announced the start of a trial with starch-based carrier bags at a handful of stores. These use a tapioca starch-derived polymer which will not degrade in the open or in the rain, but is compostable, so that this too is aimed at encouraging composting.

The Belgian market for organic waste bags is reported to be one of the largest, and here 10% of all refuse sacks sold are believed to be biodegradable. It is also reported that biodegradable bags have up to 2% of the whole plastic bag market in France: sales are mainly to local authorities and reported to be strongest in areas of natural beauty that depend heavily on tourism. Uptake is apparently slower in Germany because of regulatory issues, but a number of producers are active here. Production levels are reported to be a few million bags per year at
most. One major trial has taken place in Germany, in the town of Kassel, providing one of the few sources of measured information about potential impacts on recycling systems. The Norwegian converter Polar Gruppen has distributors in all the Nordic countries as well as Austria and Belgium, and is reported to take as much as 50% of Novamont’s Mater-bi™ production. As with other “green” initiatives, activity seems to be greater in Northern than Southern Europe, with little evidence reported of extensive uptake of biodegradable bags for retail use or for waste disposal in Spain, for example.

Some producers are having considerable success with biodegradable plastic bags for more specific applications: giveaways for trekkers traveling to the developed world, and dog faeces collection bags are among those mentioned.

While there are some sales of biodegradable carrier bags outside the UK, they have found particular success in the UK. One factor is likely to be the low price of the degradable PE product, but since the main UK processor reports little export business to mainland Europe, there must be other considerations. One suggestion is that the perceived environmental benefit of this material is less in situations where waste incineration for energy recovery is common, as it is across mainland Europe and Scandinavia. In this waste management scenario, low-grade plastic waste represents a good fuel: indeed one Scandinavian respondent to our research noted that plastics collection in much of Sweden now takes dense plastics only, with use as fuel accepted as the most sensible option for the remainder. There is clearly little point in taking the trouble to use a biodegradable polymer if the carrier bag is an intermediate stage in the path of hydrocarbon from oil well to furnace.

4.4 Consumer attitudes and behaviour

The following extract is from a Press Release issued by the UK Department of the Environment, Transport and the Regions in October 2000, and provides some idea of the scale of plastic bag consumption in one European country – the UK - and of what consumers do with them after their first use.

“According to research out today from the Department of Environment, Transport and the Region’s “Are you doing your bit” campaign, the supermarket carrier bag is the bag that most people would choose to be seen using again and again in public for everything from carrying their gym kit to a stroll down the High Street.

New research has revealed the supermarket carrier bag to be the most popular plastic bag to re-use – even more popular than designer bags such as Harrods or Gucci, and bags from fashionable high street stores like Gap and Next.

UK shoppers use eight billion plastic carrier bags – in other words:

- 323 for every household in England
- 134 for every person in the UK
- and enough to cover an area almost 200,000 times the size of Oxford Street.
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The survey results showed that, when people choose to re-use their plastic bags\textsuperscript{11}:

- 52% of people prefer to re-use a supermarket plastic carrier bag for high street shopping
- 43% of people prefer to re-use a supermarket plastic carrier bag to carry books or materials to work, school or college
- 39% of people prefer to re-use a supermarket plastic carrier bag to carry their gym kit

However, despite the many uses of the supermarket carrier bag, the survey showed that we still need to ‘do our bit’ more to cut down on unnecessary waste. On average, nearly 1 in 5 of people in each situation surveyed preferred not to reuse carrier bags – and with the average carrier bag taking many years to decompose, this could lead to problems in years to come.

Consumer attitudes to biodegradable packaging were studied in Germany as part of a broader research project on degradable polymers. Perhaps unsurprisingly in environmentally active Germany\textsuperscript{12}, one survey in the project found that 89% of people thought it a “good” or “very good” idea to replace conventional plastic packaging with biodegradable packaging. Producers of biodegradable materials also report strong consumer acceptance where secondary use of biodegradable plastic bags for organic wastes destined for composting has been possible. How consumers view them in other conditions, such as those that exist in the UK, appears not to have been studied (Foster 2003).

4.5 Conclusions

To summarise, the use of biodegradable plastic bags in Europe is clearly growing. At this stage usage can be summarised as being in “niche markets”. The high cost of most biodegradable polymers relative to conventional materials presents a significant barrier to faster uptake.

Producers seem to see the greatest opportunities in situations where the bags are used to contain biodegradable waste destined for composting, having been either expressly distributed for the purpose or diverted to it as a convenient secondary use for packaging that originally contained another product. The European Union Landfill Directive is a particularly strong force encouraging the future proliferation of such situations in Europe. There is also general agreement among environmental groups, consumers and other outside observers that biodegradable plastic bags offer genuine environmental benefits in this case, especially if the bags are made from renewable materials. At present there is a considerable financial price to be paid for these benefits: projections made for the Kassel trial suggest, however, that the price of biodegradable packaging can be expected to fall from 3 – 5 times to perhaps 1.2 - 1.5 times that of conventional packaging as production volumes of biodegradable materials increase.

\textsuperscript{11} Percentages are of people who find themselves in each situation, who expressed a preference and who chose to use or reuse a plastic bag. Research carried out by NOP.

\textsuperscript{12} Recent “Eurobarometer” research suggests that although citizens of Southern European countries are becoming increasingly concerned about environmental damage, those in Northern European countries continue to have more faith in their own ability to improve the environment through their individual actions. See Eurobarometer 58 – European Attitudes to the Environment, Dec.2002
Europeans are also using biodegradable plastic bags where composting is not their most likely fate. The nature and scale of any environmental benefits arising in these situations remain contested. Most (even producers) seem to accept that biodegradable plastic bags represent a small improvement over conventional bags at best in this case, and that their introduction should be accompanied by consumer education to avoid litter problems being exacerbated.
5 Effect of Degradable Plastic Bags in Disposal Environments

5.1 Degradable bags in landfills

5.1.1 Literature review

Many end users believe that degradable plastic products will degrade in landfills; however, degradation in modern landfills usually does not occur (Garthe and Kowal 2002). Landfills are designed to block out air, water, and sunlight. While blocking out these natural elements prevents landfill contaminants from entering soil and drinking water supplies, it also prevents degradation from taking place. Even highly organic materials, such as newspaper and food scraps, can take years to fully degrade in landfills. Because plastic material is tough and durable, it is even less likely to degrade. It is important to note, however, that not all landfills operate at optimal conditions, and some natural elements may enter certain landfills. The wide variations in the construction and operation of landfills make it difficult to draw a general conclusion about the degradability of degradable plastics in landfills (Garthe and Kowal 2002).

Polymer and bag producers involved with starch-based materials such as Mater-Bi™ claim that they do break down in landfill “eventually”, whether by slow biodegradation or by dissolution. Since it is not intended that these products be disposed of in this way, little can be stated with any more confidence than this. Advocates of degradable polyethylene claim that this material breaks down in landfill in 18 months – 3 years. According to users of these bags, these claims are backed up by independent research, and this has clearly satisfied some organisations with high environmental profiles such as the Co-Op and RSPB in Britain. It is claimed that this breakdown reduces the amount of organic waste, which becomes effectively “entombed” in landfill and so allows better use of landfill space. As the limits on landfilling of biodegradable waste enshrined in the Landfill Directive begin to take effect in Europe over the next few years, this benefit will be of decreasing relevance (Foster 2003).

The rate of polymer degradation is dependent on the material thickness and the amount of bacteria present (Biby 2002). Landfill simulations over a 19-week period show test bottles experienced a weight loss ranging from 30% with oxygen present to 80% with no oxygen present. The fact that PHVB decomposes more rapidly without oxygen present is significant because oxygen is not present in modern landfills (Biby 2002).

Many waste materials (e.g., food wastes, garden wastes, paper) that are known to be biodegradable persist in the landfill environment for many years in spite of significant microbial activity within them. This is partly because so much of this waste is enclosed and encapsulated in bio-inert, impervious plastic bags and films that impede the flow of gases and liquids and reduce the possibilities for aerobic biodegradation. Such microenvironments formed by plastic bags reduce the rate of biodegradation of foodstuffs and putrescibles. Such pockets of retardation reduce methane harvesting potential of landfills, consume increased landfill space and entrap air that inhibits landfill compaction. This problem is compounded by the common habit of many households to reuse check-out bags as kitchen tidy bags or bin liners.
All landfills change from aerobic to anaerobic conditions at any given place as the depth of garbage above that place increases. There are several advantages to encouraging as much aerobic biodegradation as possible of the organic matter disposed of in landfills before anaerobic conditions develop. Conversion of the carbon in the waste to carbon dioxide instead of methane and rapid reduction of the waste volume in order to prolong the useful life of the landfill are two such advantages.

Biodegradation of plastics is highly dependent on the type of disposal environment. For example, even natural polymers such as cellulose do not biodegrade in peat bogs. This is because peat bogs are highly anaerobic and the peat breakdown products are toxic to microbes. For this reason, humans buried in peat bogs for many thousands of years can be recovered well preserved (Gallagher 2003). Similarly biodegradable polymers disposed of in environments that are highly anaerobic or not colonized with microbes will not degrade appreciably.

It is possible that degradable plastics go some way in eliminating the 'micro-environments' that conventional shopping bags create when filled with food scraps and placed in a landfill. Conventional bags do not degrade and therefore create micro-environments that retard food biodegradation. Such pockets of retardation reduce methane harvesting potential of landfills, consume increased landfill space and entrap air that inhibits landfill compaction.

Conditions in landfills however are often anaerobic and not suitable for degradation to occur, for example newspapers dated over 30 years old have been uncovered from landfill still intact. (Rathje 1992). Further it is not always desirable for the content of landfill sites to continue to degrade over an extended period as this could lead to instability and subsidence problems once the landfill has been capped and used for another purpose.

5.1.2 Potential impacts in Australian landfills

Two key issues in assessing potential impacts in Australian landfills are:

- Whether or not bags that are designed to be degradable in certain conditions, actually degrade in landfills; and
- Whether degradability of products in landfill is an advantage or not.

In general, landfills in Australia are designed to minimise degradation. They are lined to minimise flow of groundwater into the landfill and flow of contaminated leachate out of the landfill. They are covered and compacted, which restricts the amount of oxygen present. The limited amounts of oxygen and water available in landfills therefore restrict the amount of microbial activity that would normally promote degradation. Emissions of carbon dioxide and methane over the life of the landfill are also minimized after an initial period of degradation and methane capture.

Wet ‘Bioreactor’ treatment of landfills is being trialled in NSW and Queensland. This involves constant recirculation of leachate to promote degradation, which means that the landfill stabilizes faster.
According to the literature, some degradation of organic material occurs at the surface of modern landfills, which tend to be aerobic. Organic materials start to decompose to carbon dioxide, until the weight of new material above them changes conditions from aerobic to anaerobic. At these levels degradation slows down considerably.

Degradation in most Australian landfills is only an advantage while they are being filled, and assuming that any methane is captured for energy generation rather than released into the environment. Methane is a major contributor to global warming.

5.2 Degradable bags in Compost

Composting is a specific type of microbiological treatment (MBT), a term which can be used to describe several distinct technologies:

- Aerobic composting (commercial facilities or home composting);
- Anaerobic treatment / gasification; or
- A combination of aerobic and anaerobic treatment.

These technologies can be applied to either municipal solid waste (MSW) or source-separated waste. The literature review and discussion that follows on potential impacts in Australia will consider impacts in each of these situations.

5.2.1 Literature review

A detailed literature review is in Appendix 2 and is summarized below.

Various studies have shown that starch-based plastics do biodegrade under controlled composting conditions. This has been demonstrated for bags from cornstarch and PCL, and for Mater-Bi in particular (Kaiser 2001, Booma 1994, Chiellini 1996, Piccinini 1996). These studies found no toxic residue from the degradation process.

The degradation of polyethylene (PE) modified with TDPA™ pro-oxidant additives from EPI has been assessed by a variety of laboratory-scale and field-scale tests. One study by Chiellini (2003) found that the resin did undergo ultimate biodegradation (i.e. mineralization) in simulated soil burial but not readily in composting conditions. The author notes, however, that the completeness of biodegradation and the time for oxidation are still unanswered questions.

A commercial scale composting trial of PE modified with TDPA was recently undertaken in Austria. The facility (Vienna Neustadt) involved composting in 2 stages: a forced aeration tunnel process followed by an outdoor, open windrow composting stage. The results show that the EPI additives are oxidatively biodegradable under composting conditions, yielding high quality compost with no toxic residues (Billingham 2002).

Currently, oxo-biodegradable resins do not meet ASTM’s D6400-99 standards, because they degrade through chemical oxidation before the onset of biodegradation and mineralize at a slower rate, although "The ASTM has accepted EPI’s proposal for alternative test method development, according to Graham Swift, a member of the ASTM subcommittee for polymers..."
and a consultant for EPI who has been working on alternative test methods to submit to the ASTM” (BioCycle 2002).

William Hogan, president of Willow Ridge who produce the PDQ prodegradant additive masterbatches, says the 12-week requirement for full biodegradation laid down in current ASTM composting standards is relevant only when the goal is disposal in an engineered composting facility—very few of which exist in the U.S. Hogan argues that nine months to five years is a meaningful time frame for degradation in most real-world situations (Leaversuch 2002).

There is currently little evidence to show that polymer residues in the soil are harmful. In fact the contrary appears to be true. 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 (Gallagher, 2001).

Toxic contamination is an issue that must be addressed before degradable plastics will be fully accepted for composting. Many of the additives in plastic material-plasticizers, coloring pigments, stabilizers, and degradation promoters-can contain heavy toxic metals, which can make the entire compost pile unusable (Garthe and Kowal 2002). The analysis of the heavy metal content of five different biodegradable garbage bags showed that the polymers themselves contained very low amounts of heavy metals. However, the printing with green and blue colours with copper pigments was increasing the copper content in all products (Kaiser 2001).

Prodegradants in the EPI degradable plastics (and analogues by other manufacturers) include additives based on transition metal ions (Mn, Cu, Fe, Co, Ni, Ce) and metal complexes (e.g. cobalt stearate, cerium stearate), which render conventional PE susceptible to hydroperoxidation. The critical point is that only trace quantities of Mn, Cu, Fe, Co, Ni and Ce are added to the polymer and that these mirror the trace elements present in most soils. Most are present in minute quantities and some are essential for plant growth. Nickel is toxic but also present in some quantity in most soils (Gilead 1995: 196). Research studies have concluded that the impacts of nickel from degradable plastic mulch films on plants is likely to be insignificant (Gilead 1995: 196; Fabbri 1995: 214).

A comparison of times for different materials to degrade in composting is shown in Figure 2 Comparison of composting times. This is an indication of time required for composting of various polymers, based on ‘an intermediate level of technology as observed in actively aerated and mechanically turned hall composting’ (Weber 2000: 33).
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Figure 2 Comparison of composting times

One notable exclusion from Figure 2 is the modified polyethylene. This material is not in fact described as “biodegradable” by producers – rather it is described as “degradable”, reflecting the fact that breakdown involves one or all of oxidative, thermal or photolytic decomposition (processors of this material are less than fulsome on this point). This material is claimed to break down in compost systems, taking from 4 to 16 weeks, but it does not meet EN 13432 requirements, apparently because the initial breakdown rate is too slow. There are some who assert that this material does not degrade completely to CO₂ and water, but this is refuted by producers (Foster 2003).

Soil burial

A number of studies have been performed measuring the rate of degradation of degradable plastic bags when buried in soil. The rate of polymer degradation is very dependent on the polymer type, material thickness and the amount of bacteria present (Biby 2002).

Hoshino et al. (2002) placed five biodegradable plastic bags in soils for one year at nineteen sites in Japan. Among the biodegradable plastic specimens were PHB/V, PCL, PBS, PBSA and PLA. The study results suggested that the molecular structure of the PHB/V specimens changed after one-year placement in soils. In contrast, although weight loss, and/or a decrease in tensile strength and elongation were observed after the placement in soils for the PCL, PBS,
PBSA and PLA specimens, the analyses of these specimens did not reveal any changes in their molecular structure.

The degradation behaviour of three commercial biodegradable plastics, PHB, PBS (Sky Green™) and Mater-Bi™, was studied in forest soil, in sandy soil, in activated sludge soil, and in farm soil at 28, 37 and 60°C respectively by Kim et al (2000). Biodegradation of all three polymers was most active in the activated sludge soil.

Both Sky Green and Mater-Bi showed higher degradability at 28°C than at 37°C. Biodegradability of PHB was highest at 37°C, while degradation of Mater-Bi occurred reasonably well at 60°C (Kim et al. 2000).

5.2.2 Potential impacts in the Australian composting industry

Key issues in assessing the potential impacts of degradable bags in composting in Australia include:

- The availability of composting facilities in Australia, both today and in the foreseeable future;
- The likelihood that degradable bags will actually end up in composting facilities; and
- The degradation behaviour and possible residuals from degradable bags in composting facilities.

Facilities are in operation in Australia to process mixed or source-separated organics in aerobic or anaerobic conditions. Recovery of organics is likely to expand in the future as State and Local Governments continue to move away from landfill as the preferred waste management option.

Conventional plastics bags are a problem in commercial composting operations because they do not biodegrade. The persistence of plastics causes a visual problem in the compost product and reduces its applicability and hence its commercial value. As council composting of household waste becomes more prevalent, this may increase demand for biodegradable polymers in the form of compost bags and food scrap bags. For example, a major European producer of biodegradable polymers, Novomont (Mater-Bi™), receives the majority of its revenue from compostable food bags and has a 10,000 tpa production plant servicing this market.

Oxo-biodegradable polymers (with prodegradant additives) are designed to break down under the influence of heat and UV light. Final biodegradation takes place through the action of microorganisms, although there still appears to be some uncertainty about the time needed to fully degrade (particularly whether it can occur within the normal commercial composting period) and the environmental impacts of prodegradant additives based on iron or cobalt compounds. They currently don’t meet the ASTM Standard for compostable plastics, which requires 60% mineralization of degradable polymers within 180 days (the European standard requires 90% mineralization).
In conclusion, the impacts of degradable plastics in composting facilities will become more critical as source-separation of organics for composting expands in Australia. The quality of the end compost product is critical to market success, so any contamination with plastics is a potential problem. Starch-polyester blends (e.g. Mater-Bi) meet current international standards for compostable plastics, but PE – prodegradant plastics (e.g. TDPA) do not. While they may biodegrade eventually in compost conditions, they do not currently meet the time limit for the ASTM standard (180 days). The degradation of starch – polyethylene (e.g. Earthstrength) in composting facilities will depend on the ratio of starch to polyethylene. There is a similar risk with these plastics that residual plastic will still remain behind in the compost when it is ready for sale to the market.

5.3 Potential impacts on the Recycling Stream

5.3.1 Plastic bag recycling

While recycling of supermarket shopping bags remains low at only 5%, there are a number of indicators that this is likely to increase in the short to medium term.

In August 2003 the Environment Protection and Heritage Council (EPHC) agreed to accept a revised Code of Practice developed by the Australian Retailers Association on the management of shopping bags. Retailers have agreed to ambitious targets including a 50% reduction in the number of HDPE shopping bags used. The revised Code of Practice for Shopping Bags is likely to include a 15% recycling target for HDPE shopping bags if collection is only from the supermarkets themselves, and 30% if bags are also collected from kerbside.

The plastic film recycling market is well established in Australia. There are a number of reprocessors in Australia and there is a strong market both in Australia and overseas for plastic film. Plastic shopping bags are currently collected from supermarkets in conjunction with the collection of the shrink-wrap and other commercial and industrial (C&I) film scrap. Due to the lightweight and low material use in shopping bags, they need to be collected in conjunction with C&I film scrap to make the collection commercially viable (Pym 2003).

Kerbside collection of shopping bags is also commencing in some parts of Australia. For example, a number of councils in South Australia have added plastic bags to kerbside collections. Riverina Eastern Regional Organisation of Councils (REROC) Waste Forum has co-ordinated a project to collect bags for 13 councils, including Wagga Wagga City Council, in New South Wales. The project involved the resident exchanging 20 plastic bags for one calico bag. Both REROC and individual councils have found the outcomes to be better than anticipated, and the project was well received by residents (McCleveran 2003). Wagga Wagga City Council is still collecting the bags within their kerbside collection (McClaren 2003).

Plastics Granulating Services (PGS) believes that there is a strong market for the expansion of plastic film recycling. PGS has estimated that 6000 tones of C&I waste, including plastic bags, could be diverted from landfill in South Australia each year. The company is setting up a venture in conjunction with Amcor to receive plastic waste from Adelaide City Council to commence in December 2004 (Scherer 2003).
In the context of current efforts by the plastics industry and retailers to increase bag recycling, there is significant debate occurring on the potential impact that degradable plastics could have on the recycling industry. It is generally accepted that starch-based polymers are not compatible with recycling. For example, starch-based biodegradable plastics form clumps in the melt, and degradable additives in the products could release catalytically active metal ions during reprocessing (Garthe and Kowal 2002).

Polyethylene containing starch and linear polyesters (hydro-biodegradable polyesters) are hydrophilic, that is they have an affinity for moisture. When this material is reprocessed with recycled polyethylene the resultant film can contain numerous defects such as gels.

The starch containing polymers can absorb 1-2% moisture from the atmosphere and during reprocessing by melt extrusion this water volatilizes in the extruder causing foaming of the extrudate, gels and defects in blown films and poor surface appearance in moulded products.

While the impacts of these polymers on recycling appear to be fairly clear, there is still considerable uncertainty and debate about the potential impacts of polyethylene with prodegradant additives on recycling. This is the polymer already used for shopping bags by Ritchies Supermarkets and under consideration by a number of other organisations for bag applications.

The different perspectives and available information is summarized in the following sections.

### 5.3.2 Prodegradant manufacturers

There are many types of available on the market, including TDPA™ additives produced by EPI (the system currently used in Australia), Degrade™ by Evergreen and PDQ by Willow Ridge. There is very little independent literature available on the impacts of these additives on recycling, with the exception of one study by Eyenga *et al* (2001). This study tested polyethylene with Degrade™ additives using a multi-extrusion test for recycling. The resin was processed five times through an extruder. The results were very positive, showing virtually no change in Melt Flow Index (MFI), an indicator of mechanical properties, as a result of processing. Degrade™ is an anti-oxidant and quite different to additives based on metals (such as TDPA™).

William Hogan, president of Willow Ridge, has stated that their additives do not impair recycling efforts. Hogan says markets for degradability invariably are not ones where significant recycling is likely to occur. He also says rates of incidental "recapture" of degradable products are far too low to adversely affect recycled feedstock quality (Leaversuch 2002).

The latest documentation from EPI (EPI, 2002) states that the impact of the EPI additives on the stability of recycled PE has not been properly studied to date. The company has issued a bulletin (EPI, 2002) on this topic, which states:

"EPI Environmental Plastics Inc. understands the concerns of manufacturers who fabricate and utilize recycled plastic materials that biodegradable plastics and plastic substitutes may contaminate and render useless recycled plastics feed stocks. This concern is entirely justified
for materials such as linear polyesters and bio-based starch materials, but it is NOT a concern for polyolefins modified with TDPA® additives."

The bulletin goes on to say:

"TDPA® modified PE products such as grocery bags and stretch films (products that normally end their useful life in landfills and may be good candidates for recycling) do not present a problem because they normally contain very small concentrations of the pro-degradant. While we have not conducted tests specifically for recycled plastic lumber, tests for other purposes and our understanding of addition rates required to promote degradation provide compelling evidence that “dilution” when recycled with other ordinary plastics will totally mitigate the additives’ effectiveness."

Dilution of Degraded TDPA® Modified Plastic Products a Major Factor

Let us consider a “worst-case” scenario in which some TDPA polyolefin that has undergone significant oxidative degradation is accidentally included in a batch of post consumer plastics that have been collected for recycling. This isn’t likely to happen often, but assume that some plastic bags or wrapping film that have been exposed to sunshine for 6 months as litter are inadvertently collected. This is equally unlikely to happen with ordinary polyolefins, but the answer is the same with either material. The “dilution” factor ensures that the products of recycling will not have a stability problem because the blending of small amounts of degraded polyolefin with large amounts that aren’t degraded results in a material that will have a normal stability. It has been demonstrated by work done at the National Research Council of Canada in 1970, and published by Drs. D. M. Wiles and D. J. Carlsson, that a PP film that had been photooxidized to brittleness (with a UV lamp) regained its original mechanical properties as soon as it was re-fabricated at the melt.

Most plastic products that incorporate TDPA® will have a disposal method that will ensure the TDPA® Modified Product does not end its useful life in recycling. The compost application is a good example of this as the product is designed and used specifically for commercial composts. Many degradable applications are designed and used specifically for landfill disposal. The economics of paying more for a plastic product to perform a specific function with specific disposals methods will help drive this fact. However, there will be products that will end up as post consumer recycled material.

Dilution is the most important factor that will allow TDPA® Modified plastic products to be successfully recycled without negatively impacting the post consumer recycled materials output. There are four main issues to consider:

1. Use of TDPA® in modifying plastic products does not change the mechanical properties of the plastic product or the mechanical properties of the output of the post consumer recycled material.

2. The TDPA® prodegradant is added in such small amounts that it is very easily diluted to the point that it is no longer effective.
3. The mere presence of the additive in such small amounts in a modified product does not cause the product to degrade/biodegrade without the start of the oxidative process by either elevated temperatures over time, UV light or mechanical stress. These conditions are not normally present until after disposal.

4. The inclusion of small amounts of degraded plastic with non-degraded plastic results in material that will have normal stability (EPI, 2002).

EPI claims to have undertaken laboratory-scale tests that show that MFI remains constant after three extrusions (Tung 2003) but this data is not publicly available as yet. They recommend that recyclers undertake their own plant trials to test the impacts of their degradable resins on recycling. The company believes that the impact of the additives will be minimal due to the small quantities used, and the dilution effect that occurs when they are mixed with conventional plastics. Potential problems could occur when the degradable bags are processed as one batch, which may occur when the bags are collected in bulk from supermarkets using the bags. This is acknowledged by EPI, who recommend that batches of degradable bags should be blended at less than 50% with other plastics (Tung 2003).

5.3.3 Recyclers

Plastic recyclers are very concerned about the potential impact that degradable polymers could have on the quality of recyclate. Detmark Polybags (Dandenong, VIC.) for example is presently buying masterbatch additive from EPI and producing degradable bags for export. Ironically Detmark is also a user of recycled polyethylene shopping bags and is very concerned about the potential impact that ‘slugs’ of degradable bags will have on the recycling process and quality of their recyclate. Detmark is particularly concerned about the negative impacts on the recycling market (Davidson, 2003). Detmark currently use approximately 30 tonnes / month of plastic check out bags in the production of new check-out bags. This volume is expected to grow to 200 tonnes over time. Detmark’s concern about degradable bags in the recycling stream is that they will inevitably enter the PE plastic stream (they have already appeared in limited quantities) and that they are not identifiable (Davidson 2003).

Plastic Granulating Services (PGS) is one of the largest plastics recyclers in Australia, and they also have serious concerns that degradable bags and films will contaminate their plastic streams for reprocessing. If degradation problems occur then PGS is prepared to reject the entire feedstock stream. The larger potential impact of the prodegradant-containing systems beyond that of destabilizing large quantities of recycled plastic is that the buyers of plastic recyclate will lose confidence in the integrity of the scrap plastic and simply not buy it (Scherer, 2003).

PGS is worried that the prodegradants will destabilize their products, resulting in costly failures and customers losing confidence in the quality of their building and agricultural film products. Their main worry is that they have no control over the material coming into the plant. PGS has already advised Amcor, who collect scrap plastic from Ritchies Supermarkets, that they do not want any of that stream (Scherer, 2003).
Recycled PE is largely used in manufacture of agricultural piping, builder’s film and plastic lumber. If used in plastic piping, the degradable films for example could create sections in the pipe that are susceptible to accelerated degradation. Plastic pipe manufacturers currently use large quantities of recycled polyethylene. This is usually not disclosed to producers. With the recent introduction of the degradable plastic bags, the plastic pipe producers are becoming very nervous about the longevity of their products (multiple industry interviews 2003).

Astron the largest polyethylene recycler in Australia and New Zealand is extremely concerned about the potential impact of degradable plastics on their polyethylene recyclate production (Astron, 2003). Much of their production is used in the film and poly pipe industry. The following extract demonstrates the concern that Astron have with the introduction of degradable polymer systems.

“As you can imagine, no purchaser of plastic resin would want such a process anywhere near products they buy. Any suggestion that such material had an on-going reaction within some recycled resin you purchased, would render a claim on the poor unsuspecting recycler ….. Imagine a masterbatch being made using a recycled resin with an unintended degradable resin component, after being used as a purge material, or even part of the base. Say, this masterbatch is then used to colour a resin for a pipe product. The resin for the pipe manufacturer could well come for us as a recycler where we carefully worked to ensure no degradable resin was in our product. But all this is undone because of the colorant either we used, or the pipe manufacturer used, to meet a colour specification. In the field, degradation is accelerated and the product fails sooner than warranted. Then, everyone is in trouble, as customers down the line look to their suppliers to find out the cause of the early failure. The market implications for recycled resin could be truly serious” (Astron, 2003).

“We recyclers know that degradables are coming in volume. We hope the regulators can take some action to ensure such materials are colour-coded to enable easy identification and exclusion from the recycling waste streams. To be effective, colour-coding would have to be made mandatory to have any practical effect. In the end, recycling is a loop process - source, reprocess, re-use, source, etc” (Astron, 2003).

“The recycling process breaks down … when something is added to make re-use impossible. Then it becomes ‘waste management’. In fact, that is what degradable plastics do - they are another approach to ‘waste management’. They make no contribution to ‘recycling’. If anything, they actively undercut the economics of recycling. And that, essentially, is why recyclers look on with considerable trepidation at the public and private drive to adopt degradables technology as a way to deal with society’s plastic waste.” (Astron 2003).

Visy Recycling is not currently recycling plastic bags, but is one of Australia’s largest plastic recyclers. Their view is that plastic bags have good potential to be collected from kerbside as well as from supermarkets, and that degradable plastics (both prodegradants and starch-based plastics) are not compatible with recycling (Kosior 2003).
5.3.4 Potential impacts

There is a risk that degradable plastics containing prodegradant additives (such as TDPA™) could have a negative 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 sensitizing polyolefins towards oxidative degradation that even low levels of such cross-contamination has the potential to destabilize a large volume 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 in the field where the loss potential and consequential damage would be highest.

Environmentally degradable plastics by their very nature are designed to breakdown under the influence of heat, light and/or moisture. Given this, degradable plastics have the potential to destabilize and compromise the properties of recyclable polymers if they enter the plastics recycling stream. In particular, masterbatch additive type degradable plastics contain prodegradants and if such degradable plastics enter the recycling stream they may cause catalytic or sensitized degradation of recyclable commodity plastics. The consequential effect of this may be premature failure or a reduction of the structural integrity of recycled plastic pipe, plastic bins and crates and film/sheeting products.

The potential impact of prodegradant-containing plastics on the plastic recycling stream can be mitigated through the use of chelating additives, which bind up the catalytic metal ions so they cannot exert their prodegradant effect. Such additives are already used in the wire and cable industry to protect polyethylene insulation from the prodegradant effects of copper ions. Such additives sequester the metal ions to form stable, non-reactive complexes. In addition, the destabilizing action of prodegradant plastics can be largely offset by restabilization and the addition of supplementary antioxidants to the recyclate.

Manufacturers of prodegradant additives claim that their product does not have a negative impact on recycling due to the small amount used, and the ‘dilution affect’ once the bags are mixed with other film and bag products. While there is some evidence that anti-oxidant additives (such as Degrade™ used by Evergreen) do not reduce the quality of recyclate, even after repeated processing (Eyenga et al 2001), there is no published evidence that others (e.g. TDPA™ used by EPI) have similar impacts. This needs to be tested through plant-scale trials with bag recyclers.

There is need for further research on the impacts of degradable polymers, particularly the prodegradant additives, on recycling. Current assurances provided by manufacturers may be correct, but they need to be independently tested and verified. At this stage, a precautionary
approach would seem appear to justify the removal of degradable bags from recycling to avoid the potential for product failure.

5.4 Degradable bags in the litter stream and marine environments

5.4.1 Literature review

Professor Guillett from the University of Toronto has devised a mathematical model to show that the most effective way to reduce the accumulation of litter is to reduce the lifetime of the plastic being littered (Guillett 1995).

Even though marine disposal is not typically considered a method to manage wastes, thousands of plastic bags enter the beaches and oceans every year. There is a possibility that degradable plastics can reduce this threat by decreasing the strength and life span of the plastic material. The main area where biodegradable plastics can make a contribution here is as bait bags.

Biodegradable plastics are very appropriate for fishing bait bags which are frequently discarded by recreational fishermen. Australia is at the forefront of using biodegradable plastics in bait bag applications. Biodegradable bait bags are being commercially produced (by R.F. MacGloclan, Moorabbin) from Mater-Bi™. Extensive testing has been performed by Flinders University (S.A.), EPA (Queensland), RecFish Organization and Seaworld on the Gold Coast (Hall 2003). Seaworld tested the bags by wrapping them in Gutter-Guard™ and then immersing them in sea water tanks and measuring the time of progressive weight loss. The Australian bait bag was officially launched at Seaworld in June 2003. Flinders University has conducted sea water testing of Mater-bi bait bags and recorded a 10% weight loss in 3 weeks.

Besides degrading in seawater, biodegradable bait bags must also pass stringent mechanical tests such as property retention after storage in deep freezers and durability during cold transport (Hall, 2003). The new bait bags will be phased in over the next two years and non-degradable PE baits will be progressively phased out. All major bait bag manufacturers (e.g. R. F. Mac., SA Bait Supply, WA Bob Walkley and Tweed Bait) have all endorsed the biodegradable bait bag despite the fact that Mater-bi is $8.70/kg while conventional polyethylene is $1.50/kg (Hall 2003).

It is well known that sea turtles 'see' plastic bags as jellyfish and that dead sea turtles have been found bloated with plastic bags in their digestive tract and gut. Novamont (Italy) have conducted in vitro tests with Mater-Bi™ in solutions simulating the digestive juices of sea turtles. Guidance for this project was given by an Australian expert on sea turtles Colin Limpus, Queensland EPA Conservation Science Department. The testing was carried out in-house at Novamont using solutions that mimicked the chemical nature of the turtle's gastric juices (Bjorndal 1996; Lutz et al. 2002).

Australian sea turtles are threatened species since only one in every 1000 female eggs gets to sexual maturity and it takes 30-40 years to get to that stage. Further these delayed maturity animals only have breeding cycles every 5 to 6 years (Limpus 2003).
Limpus believes biodegradable plastic bags are a step in the right direction but since they still take six months to degrade in seawater they are not a complete solution (Limpus 2003). He is concerned that the way the thermoplastic starch is modified in order to reduce its sensitivity to moisture and to make functional plastic bags may prevent digestive enzymes in turtles from attacking the plastic. Normally symbiotic gut flora digest cellulose (e.g. plant walls) and other polysaccharides but because the starch has been modified to make it waterproof it will be less susceptible to digestion. In theory however polysaccharide digestive processes should ultimately occur and the bags should actually be nutritious (Limpus 2003).

Limpus is trying to organize a project to study the breakdown time of biodegradable plastics in the digestive tract of turtles. However since sea turtles are threatened species he is proposing to use herbivorous fresh water turtles, which are not threatened (and physiologically similar) in a plastic feeding trial (Limpus 2003). Limpus has observed that fresh water turtles in drought conditions have been found to produce scats with plastic films fragments 5 months after digesting the plastic bags.

The rate of biodegradation of Mater-Bi in both freshwater and seawater was studied by Flinders University (McClure 1996). The study was performed on the earlier Mater-Bi formulation comprised of thermoplastic starch and polycaproactone. Biodegradation was assessed by following the reduction in dry weight of sample strips in either freshwater or seawater as well as by measuring the reduction in tensile strength of the strips over time. Tensile strength is an important characteristic in terms of potential for endangering sea animals. The results showed that breakdown was most rapid in freshwater with a reduction in dry weight of approximately 50% being achieved over 20 weeks. Reductions in dry weight in seawater were much lower (approx. 10-20%). In both media, large reductions in tensile strength were recorded (30-80% compared to the reference samples after 12 weeks) (McClure 1996). Films were also exposed to water containing mercuric chloride (a potent anti-microbial agent) in order to determine the contribution of non-biological degradation to the observed breakdown. No significant reductions in tensile strength were observed in the antimicrobial agent solutions indicating that the degradation of the polymer and loss of tensile strength was primarily due to microbial breakdown. The large reductions in tensile strength observed suggest that starch-based plastics are likely to be a lower risk to seawater and freshwater animals than conventional non-degradable plastics. However, large reductions in tensile strength required exposure periods of over ten weeks and the deliberate disposal of any waste plastics into marine or freshwater environments should be avoided (McClure 1996).

Gold Coast City council placed their first commercial order for Mater-Bi bags for dog faeces collection in June 2003. Prior to this 50,000 bags were trialed in park bag dispenser with good results. It was observed that people often threw the plastic bag and dog faeces inside in the water (beach, river or lake). Given this it is important that biodegradable bags are used.

Testing by Blackburn City Council in Victoria actually found that the Mater-bi™ dog faeces disposal bags actually break down faster in a dog septic tank inoculated with the appropriate culture than the dog faeces (Hall 2003).
5.4.2 Potential impacts in the Australian environment

A number of litter organisations were contacted for this study\(^{13}\). All of the litter groups contacted were strongly opposed to the introduction of degradable bags as a solution to the litter problem. It was felt that the introduction on degradable bags would send the wrong message to consumer and result in an increase in both the use of bags and incidence of litter.

Currently plastic bags are littered and remain whole. There is concern that the degradable plastic bags would break into pieces and while they could reduce the visual impact of litter, they could also make it harder to collect the fragments of plastic.

There is concern over the length of time it requires for the bag to be broken down. The environmental factors required to start the degradation process are not always present (e.g., heat, moisture etc) and therefore the bags would act as a normal plastic bag.

While it was agreed that the use of degradable polymers in some applications would be useful in solving some of the marine litter issues, again it was felt that this would send the wrong message to the consumer and result in a higher level of marine litter.

It should be noted that these are the informed views expressed by organizations involved in litter reduction programs. At this stage they are not supported by any independent research. There are in fact two alternative scenarios being discussed on potential impacts of degradable plastics on littering behaviour, that would need to be evaluated through further research, i.e.:

- That degradable plastic bags may increase littering if they are perceived by some people as less harmful to the environment; or
- That degradable plastic bags may reduce littering if they increase awareness about environmental impacts, resulting in changes in behaviour.

The potential benefits of degradable plastics in reducing risks to wildlife in marine litter are not clear. While the disintegration of plastics into smaller pieces might make them less likely to be ingested by larger fish or marine animals, they may be a greater risk to smaller animals such as sea turtle hatchlings.

\(^{13}\) Victorian Litter Action Alliance, Clean Up Australia, EcoRecycle Victoria, Melbourne Water, Keep Australia Beautiful Victoria
6 Life cycle assessment

6.1 Definition of life cycle assessment

Life cycle assessment (LCA) is the process of evaluating the potential effects that a product, process or service has on the environment over the entire period of its life cycle. Figure 3 illustrates the life cycle system concept of natural resources, energy coming into the system and product and emissions leaving the system.

Figure 3 Life cycle system concept

The International Standards Organisation (ISO) has defined LCA as

"a technique for assessing the environmental aspects and potential impacts associated with a product by:

- Compiling an inventory of relevant inputs and outputs of a product system;
- Evaluating the potential environmental impacts associated with those inputs and outputs; and
- Interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study" (AS/NZS 1998).

The technical framework for life cycle assessment consists of four components, each having a very important role in the assessment. They are interrelated throughout the entire assessment and in accordance to the current terminology of the International Standardization Organisation (ISO). The components are goal and scope definition, inventory analysis, impact assessment and interpretation (Figure 4).
6.2 Streamlined life cycle assessment modelled in this report

A streamlined life cycle assessment (LCA) was undertaken on a selection of degradable plastics application for film blowing into shopping bags. The degradable plastic materials that are suitable for applications in film blowing for shopping bags and/or are current available on the market that will be investigated in the current study are:

(a) Polyesters
   i. Maize starch with polycaprolactone (e.g., Mater-Bi™);
   ii. Maize starch with polybutylene adipate terephthalate (PBAT) (e.g., Ecoflex);
   iii. Maize starch with polybutylene succinate/adipate (PBS/A) (e.g., Bionelle™).

(b) Starch-polyethylene blend
   i. Tapioca starch and high-density polyethylene (e.g., Earth-strength);

(c) Polyethylene + prodegradant (e.g., TDPA-EPI); and

(d) Polylactic acid (PLA).

In Nolan ITU et al (2002) a streamlined LCA was conducted for ten shopping bags. The streamlined LCA presented in this report builds upon this previous research. The streamlined LCA will include:

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14 Singlet HDPE, 50% recycled singlet HDPE, boutique LDPE (single use), reusable LDPE, calico, woven HDPE swag, PP fibre “Green Bag”, Kraft paper – handled, solid PP “Smart Box” and biodegradable – starch based.
Discussion of previous assumptions about degradation rates of different materials that were modeled in the streamlined LCA reported in Nolan ITU et al (2002) and how they have been changed in this report;

Comparison of the environmental profile of various degradable resins most likely to be used for bag applications in Australia; and

Comparison of the environmental profile of the degradable bags with other single use bags (LDPE, HDPE, paper, and cotton bags).

6.2.1 Goal of the study

The goal of the study is to understand the life cycle environmental profile of degradable plastics in the application of film blown bags (i.e., shopping bags) and how they compare with alternative materials such as HDPE, LDPE, paper and calico.

6.2.2 Functional unit

The function of the study is the use of shopping bags to carry groceries and goods from a store to home. The number of single use bags required and the number of reusable bags required to carry goods home per person per year were calculated.

Any comparison of life cycle environmental impacts must be based on a comparable function. For the purpose of this study, the ‘functional unit’ for this review has been defined as a household carrying approximately 70-grocery items home from a supermarket each week for 52 weeks.

6.2.3 System boundaries

Figure 5 provides illustration of the system boundaries for the streamlined study.

6.2.4 Data sources

Data sources used in this streamline study were from publicly available life cycle inventory data.
Figure 5 System boundaries of the study

Coal mining and electricity generation

Crop growing and harvesting

Petrochemical production

Oil and gas production and exploration infrastructure

Starch extraction

Monomer production

Polymer production

Film blowing

Bag at retail outlet

Use by consumer

Disposal of bag

Reuse of bag

Recycling

Organic treatment

Landfill

Litter

Avoid HDPE singlet bag

System boundary for streamlined LCA
Table 9 lists the composition of the degradable polymers as they have been modelled in the streamlined LCA. Additional information on each polymer is presented in Appendix 3.

**Table 9 Composition of degradable polymers modelled in the streamlined LCA and assumption made**

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Composition1</th>
<th>Assumptions made</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Starch-polyester blend (e.g., Mater-Bi)</td>
<td>50% starch from maize 50% polycaprolactone (PCL)</td>
<td>Maize growing based upon data related to growing maize in the Netherlands. PCL is produced from cyclohexanone (95%) and acetic acid (5%) (Composto 1998).</td>
</tr>
<tr>
<td>2. Starch Polybutylene succinate/adipate (PBS/A) (e.g., Bionelle™).</td>
<td>50% - starch from maize 25% - 1,4- butanediol 12.5% - succinic acid 12.5% - adipic acid</td>
<td>Adipic acid is manufactured from cyclohexane (40%) and (60%) nitric acid (US EPA 1991). Succinic acid is formed through the fermentation of corn-derived glucose.</td>
</tr>
<tr>
<td>3. Starch with polybutylene adipate terephthalate (PBAT) (e.g., Ecoflex)</td>
<td>50% - starch from maize 25% - 1,4- butanediol 12.5% - adipic acid 12.5% - terephthalate acid</td>
<td>1,4-butanediol is derived either from natural gas or corn glucose (Pennington et al. 2001).</td>
</tr>
<tr>
<td>4. Starch-polyethylene blend (e.g., Earthstrength)</td>
<td>30% starch from cassava (tapioca) 70% high-density polyethylene</td>
<td>Cassava growing based upon data related to growing cassava in the Netherlands.</td>
</tr>
<tr>
<td>5. Polyethylene+prodegradant</td>
<td>97% high density polyethylene 3% additive</td>
<td>Additive modelled as stearic acid and small amount of cobalt metal to represent the presence of cobalt stearate.</td>
</tr>
<tr>
<td>6. Polylactic acid (PLA)</td>
<td>100% polylactic acid</td>
<td>Based upon maize growing in the USA.</td>
</tr>
</tbody>
</table>

**Notes:**
1. The composition for each polymer is based upon materials that would be required to perform as material for film blowing and application as shopping bags (comparative in performance to the high-density polyethylene singlet bag). The streamlined LCA utilises generic life cycle inventory data for each material and do not refer to specific commercial products on the market or from companies that manufacture each polymer.
6.3 Life cycle inventory modelling

This section describes the data used to model the streamlined LCA, key assumptions made and description of end-of-life waste management modelling.

6.3.1 Characteristics of the use of the degradable polymers

The key assumptions in the modelling of the degradable plastics are presented in Table 10.

<table>
<thead>
<tr>
<th>Degradable polymers</th>
<th>Weight (g)(1)</th>
<th>Relative capacity</th>
<th>Quantity of bags per week in relation to relative capacity</th>
<th>Expected life</th>
<th>Quantity of bags per year adjusted in relation to expected life</th>
<th>Transport to Australia (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mater-Bi bag</td>
<td>8.1</td>
<td>1 (6-8 items)</td>
<td>10 Single trip</td>
<td>520</td>
<td>From Italy (16,000 km)</td>
<td></td>
</tr>
<tr>
<td>Bionelle bag</td>
<td>6</td>
<td>1 (6-8 items)</td>
<td>10 Single trip</td>
<td>520</td>
<td>From Japan (8,000 km)</td>
<td></td>
</tr>
<tr>
<td>EcoFlex bag</td>
<td>6</td>
<td>1 (6-8 items)</td>
<td>10 Single trip</td>
<td>520</td>
<td>50% from Germany (16,000 km) and 50% from USA (13,000 km)</td>
<td></td>
</tr>
<tr>
<td>Earthstrength bag</td>
<td>6</td>
<td>1 (6-8 items)</td>
<td>10 Single trip</td>
<td>520</td>
<td>From Malaysia (6,000 km)</td>
<td></td>
</tr>
<tr>
<td>Oxo-biodegradable bag (PE and prodegradant additive)</td>
<td>6</td>
<td>1 (6-8 items)</td>
<td>10 Single trip</td>
<td>520</td>
<td>Concentrate from Canada (16,000 km) and 50% of bags from Malaysia (6,000 km)</td>
<td></td>
</tr>
<tr>
<td>PLA bag</td>
<td>8.1</td>
<td>1 (6-8 items)</td>
<td>10 Single trip</td>
<td>520</td>
<td>50% from USA (13,000 km) and 50% from Japan (8,000 km)</td>
<td></td>
</tr>
</tbody>
</table>

Note: (1) Mass of bags based upon that required so that it performs the same function as a HDPE singlet bag.

6.3.2 End-of-life waste management modelling

Several different waste management treatment technologies were modelled to understand how degradable plastics degrade in aerobic and anaerobic environments. Using the work from
Grant et al (2003b) the following treatment technologies were modelled (with description of each process provided in Appendix 3.

- Landfill (anaerobic environment) - baseline landfill modelled upon Victorian landfills;
- Source separated green and food MBT composting (baseline for composting);
- Municipal solid waste MBT composting; and
- Municipal solid waste anaerobic digestion.

Assumptions were made to model the baseline end-of-life waste management destinations of the degradable plastics and they are (Figure 6):

- Assume 70.5% of degradable bags go to landfill;
- Assume 10% of degradable bags go to composting (source separated organics)\(^\text{15}\);
- Assume 19% of degradable bags are reused (which replace the use of HDPE singlet bags)\(^\text{16}\); and
- Assume 0.5% of degradable bags end up as litter\(^\text{17}\).

In the landfill environment and in source separated organics composting it is assumed that the degradable polymers will degrade like food waste (i.e., 90% of the polymer will degrade).

Two different litter scenarios were modelled for each degradable plastic:

- Litter aesthetics (calculated based upon the time the bag would be litter – m\(^2\)a); and

\(^\text{15}\) While source separation of garden organics is common in Australia, there are currently very low levels of separation of other organic material (food, paper etc) for organics treatment. The assumptions about the percentage of bags disposed to landfill and compost were made by the research team taking this into account.

\(^\text{16}\) This was calculated by using the average amount of household rubbish generated per week of 14kg.14kg equals 333g/l equalling 42 litres of rubbish per week. One HDPE singlet holds approximately 10 litres therefore a maximum of 5 bags per household per week could be used as bin liners. Therefore as the average Australian household has 2.6 residents and the consumption of single use bags is just under 1 per person per day that equals approximately 16 single use bags collected per household per week. Based on the conservative assumption that 60% of householders reuse bags (note figures as high as 85% have been quoted by Nolan-ITU et al (2002: 6), the percentage of supermarket shopping bags used for this purpose would be approximately 19%. This reuse results in avoided consumption of bin liner bags, and the impact of additional bin liners has been built into the LCA.

\(^\text{17}\) The estimated percentage in litter is based on existing data relating to HDPE singlet bags entering the litter stream: of the 6 billion HDPE bags consumed annually, an estimated 30 million enter the litter stream, which equals 0.5% of output (Nolan-ITU et al 2002: Appendix A)
- Litter marine biodiversity (calculated based upon if the polymer floats and how long it would float, or if it sinks how long it will take to sink).

**Figure 6 Waste management options modelled in baseline**

The litter values used for each degradable polymer under the different litter scenarios are presented in Table 11

**Table 11 Characteristics of degradable plastics in different littering environments**

<table>
<thead>
<tr>
<th>Degradable polymer</th>
<th>Litter by area</th>
<th>Litter by mass</th>
<th>Litter aesthetics</th>
<th>Litter marine biodiversity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mater-Bi 30*20 cm = 0.06 m²</td>
<td>30*20 cm = 0.06 m²</td>
<td>8.1 g</td>
<td>Assume bag litter lasts for 6 months¹⁸ (0.03 m²a)</td>
<td>Sink in 1 day (0.0221 g/year)</td>
</tr>
<tr>
<td>Bionelle 30*20 cm = 0.06 m²</td>
<td>30*20 cm = 0.06 m²</td>
<td>6 g</td>
<td>Assume bag litter lasts for 6 months (0.03 m²a)</td>
<td>Sink in 1 day (0.016 g/year)</td>
</tr>
<tr>
<td>EcoFlex 30*20 cm = 0.06 m²</td>
<td>30*20 cm = 0.06 m²</td>
<td>6 g</td>
<td>Assume bag litter lasts for 6 months (0.03 m²a)</td>
<td>Sink in 1 day (0.016 g/year)</td>
</tr>
<tr>
<td>Earthstrength 30*20 cm = 0.06 m²</td>
<td>30*20 cm = 0.06 m²</td>
<td>6 g</td>
<td>Assume bag litter lasts for 6 months (0.03 m²a)</td>
<td>Float for 6 months (3 g/year)</td>
</tr>
<tr>
<td>Oxo-biodegradable (PE and prodegradant additive) 30*20 cm = 0.06 m²</td>
<td>30*20 cm = 0.06 m²</td>
<td>6 g</td>
<td>Assume bag litter lasts for 6 months (0.03 m²a)</td>
<td>Float for 3 months (due to prodegradant) (1.5 g/year)</td>
</tr>
<tr>
<td>PLA 30*20 cm = 0.06 m²</td>
<td>30*20 cm = 0.06 m²</td>
<td>8.1 g</td>
<td>Assume bag litter lasts for 6 months (0.03 m²a)</td>
<td>Sink in 1 day (0.016 g/year)</td>
</tr>
</tbody>
</table>

**6.4 Life cycle impact assessment results**

The environmental impact categories analysed in the impact assessment are (additional description of each impact indicator is presented in Appendix 3.

¹⁸ This is an assumption. There is limited data available on degradation rates in litter. Estimated ‘shelf-life’ is 6 months for TDPA - EPI plastics and 2 years for starch – polyester (Hall 2003). Estimates of degradation times depend on both the resin and the environment, and range from 2 months to more than a year (see Table 3)
In the following sections a description of the results will be presented for each impact category and a graph will be used to illustrate the differences between the degradable polymers. The actual values behind those presented in the graphs to follow are given in Appendix 3.

### 6.4.1 Greenhouse

Figure 7 presents the greenhouse gas emission breakdown for the six degradable polymers. Greenhouse impacts are dominated by carbon dioxide through electricity and transport consumption, methane emissions through degradation of materials in anaerobic conditions (e.g., landfill) and nitrous oxide (N\textsubscript{2}O) emissions in fertilizer applications on crops (Figure 7). Degradable polymers with starch content have higher impacts upon greenhouse due to methane emissions during landfill degradation and N\textsubscript{2}O emissions from fertilizing crops whereby methane has a 21 times higher greenhouse potential than CO\textsubscript{2} and N\textsubscript{2}O is 310 times more potent a greenhouse gas than CO\textsubscript{2}.\footnote{Farming practices modeled in the LCA are based on conventional European farming. Organic farming techniques may reduce greenhouse impacts through the use of organic nitrogen, which produces less N\textsubscript{2}O emissions.}
Some credits are given for sequestration of carbon in landfill, though are not outweighed by the other emissions. For example in the case of the Mater-Bi polymer 40% of the greenhouse emissions are a result of methane not captured at landfill and emissions during fertilizer application on the growing crop and 9% of the greenhouse credits are a result of the methane captured at landfill for biogas generation and the carbon sequestration. The impacts of cassava growing are lower than maize growing with respect to the quantities of fertilizers used (Table 12).

Table 12 Fertiliser use on maize and cassava crops per 1kg

<table>
<thead>
<tr>
<th>Fertiliser</th>
<th>Maize</th>
<th>Cassava</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertiliser CAN (17% N)</td>
<td>0.203 kg</td>
<td>0.0022 kg</td>
</tr>
<tr>
<td>Fertiliser TSP (20% P)</td>
<td>0.11 kg</td>
<td>0.0022 kg</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.044 kg</td>
<td>0.0053 kg</td>
</tr>
</tbody>
</table>

Source: IVAM 4.0 database in SimaPro 5.1.

6.4.2 Resource (abiotic) depletion

Resource (abiotic) depletion refers to the consumption of non-living resources (e.g., coal, oil, gas). The degradable plastics with a combination of starch based and conventional polymers (except for the oxo-biodegradable polymer which is 97% HDPE) perform better on resource depletion. This is due to the fact that degradable polymers that have more material based upon renewable resources such as crops therefore have a lower percentage of material based upon crude oil or natural gas, which translates into less demand upon non-renewable resources as material sources. Non-renewable resources are also consumed in the maize growing and starch extraction processes and the cassava growing that are the dominating stages of the life
cycle in the Mater-Bi, Ecoflex, Bionelle and Earthstrength polymers, though these are less than the resources as feedstock into the conventional polymers (based upon the available data in the life cycle inventory).

**Figure 8 Resource (abiotic) depletion characterisation values for the six degradable polymers**

![Graph showing resource depletion values for six polymers]

Note: Values are presented in Antimony (Sb) equivalents.

### 6.4.3 Eutrophication

The polymers that comprise more material from renewable resources (e.g., maize) have higher impacts than the other polymers because of the application of fertilizers to the land and the run-off of nutrients into waterways (Figure 9). The data also indicates that maize growing has a higher impact than that of cassava (tapioca) (see Table 12).

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20 Farming practices modeled in the LCA are based on conventional European farming. It is unclear whether organic farming techniques would reduce eutrophication impacts.
Figure 9 Eutrophication characterisation values for the six degradable polymers

Note: Values are presented in phosphate (PO₄) equivalents.

6.4.4 Litter categories

Figure 10 shows an indicator, which estimates the time in which plastic litter in marine environments has the potential for ingestion or entanglement by marine fauna. The Earthstrength and oxo-biodegradable bags are assumed to float for 6 months and 3 months respectively, while the remaining bags are assumed to sink within one day of entering the marine environment. From this indicator it can be seen that density of the material in more important than degradability (given that none of the polymers assessed dissolve in sea water) for reduce the risk of harmful impacts to marine fauna. The results for the litter aesthetic indicators are the same for all degradable bags because all biopolymers have the same assumed degradation life as litter. This indicator is more meaningful for comparisons with non-degradable bags, which is done in the next section.
6.5 Sensitivity analysis – different waste management treatment options

This section presents results on the different end-of-life options for the degradable polymers. Using the Mater-Bi material as an example, 1 kg of material was sent to five different end-of-life waste management processes – landfill, composting with source separated organics, aerobic stabilisation of municipal solid waste, anaerobic digestion of source separated organics and anaerobic digestion of municipal solid waste (Figure 11). This figure illustrates the greenhouse credit of carbon sequestration in landfill, but also the methane reduction from diverting material away from landfill and into composting or anaerobic digestion.
Similar results are obtained for the other degradable polymers except for the oxo-biodegradable polymer (PE and prodegradant additive) that does not have the methane related or N$_2$O emissions.

### 6.6 Comparisons of degradable plastics with other bags

Building upon the LCA work undertaken in Nolan et al (2002) where single use plastic and paper bags were compared with reusable plastic and calico bags, the following section presents a comparison of these bags with the degradable plastics modelled in the previous section. The key assumptions in the modelling of the degradable plastics are presented in the following tables.
### Table 13 Characteristics of the use of the degradable plastics

<table>
<thead>
<tr>
<th>Alternative bags</th>
<th>Weight (g)</th>
<th>Relative capacity</th>
<th>Quantity of bags per week in relation to relative capacity</th>
<th>Expected life</th>
<th>Quantity of bags per year adjusted in relation to expected life</th>
<th>Transport to Australia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singlet HDPE</td>
<td>6g</td>
<td>1 (6-8 items per bag)</td>
<td>10</td>
<td>Single trip</td>
<td>520</td>
<td>Hong Kong (7,000 km)</td>
</tr>
<tr>
<td>Kraft paper handled</td>
<td>42.6g</td>
<td>1</td>
<td>10</td>
<td>Single trip</td>
<td>520</td>
<td>n/a</td>
</tr>
<tr>
<td>PP fibre “Green Bag”</td>
<td>PP 65.6g</td>
<td>1.2</td>
<td>8.3</td>
<td>104 trips (2 years)</td>
<td>4.15</td>
<td>n/a</td>
</tr>
<tr>
<td>Woven HDPE “swag bag”</td>
<td>130.7g</td>
<td>3</td>
<td>3.3</td>
<td>104 trips (2 years)</td>
<td>1.65</td>
<td>Taiwan (7,000 km)</td>
</tr>
<tr>
<td>LDPE “bag for life”</td>
<td>40 g</td>
<td>2</td>
<td>-</td>
<td>10 trips (1 year)</td>
<td>26</td>
<td>n/a</td>
</tr>
<tr>
<td>Calico</td>
<td>125.4g</td>
<td>1.1</td>
<td>9.1</td>
<td>52 trips (1 year)</td>
<td>9.1</td>
<td>Pakistan (11,000 km)</td>
</tr>
</tbody>
</table>

The end of life assumptions for the alternative bags is presented in Table 15.

### Table 14 End of life assumptions for the alternative bags

<table>
<thead>
<tr>
<th>Alternative bags</th>
<th>Landfill (%)</th>
<th>Recycled (%)</th>
<th>Litter (%)</th>
<th>Reuse (as a bin liner for household waste) (1) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDPE singlet bag</td>
<td>78.5</td>
<td>2</td>
<td>0.5</td>
<td>19</td>
</tr>
<tr>
<td>Kraft paper handled bag</td>
<td>39.5</td>
<td>60</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>PP fibre “green bag”</td>
<td>99.5</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>Woven HDPE “swag bag”</td>
<td>99.5</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>LDPE “bag for life”</td>
<td>97.5</td>
<td>2</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>Calico</td>
<td>99.5</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
</tr>
</tbody>
</table>

Note: (1) Subsequently avoids HDPE bin liners.

The litter values used for each of the alternative bags under the different litter scenarios are presented in Table 15.
Table 15 Characteristics of alternative bags in different littering environments

<table>
<thead>
<tr>
<th>Alternative bags</th>
<th>Litter by area</th>
<th>Litter by mass</th>
<th>Litter aesthetics</th>
<th>Litter marine biodiversity</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDPE singlet bag</td>
<td>30*20 cm (0.06 m²)</td>
<td>6 g</td>
<td>Assume bag litter lasts for 2 years due to light film</td>
<td>Will float for 6 months (3.5 g/year)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.12 m²a)</td>
<td></td>
</tr>
<tr>
<td>Kraft paper handled bag</td>
<td>20 * 30 cm (0.06 m²)</td>
<td>42.5 g</td>
<td>Assume bag litter lasts for 6 months (0.03 m²a)</td>
<td>Assume to sink in 1 day (0.116 g/year)</td>
</tr>
<tr>
<td>PP fibre “green bag”</td>
<td>42 * 42 cm (0.09 m²)</td>
<td>115.9 g</td>
<td>Assume bag litter lasts for 5 years (0.45 m²a)</td>
<td>Assume to float for 6 months (58 g/year)</td>
</tr>
<tr>
<td>Woven HDPE “swag bag”</td>
<td>50 * 50 cm (0.18 m²)</td>
<td>130.7 g</td>
<td>Assume bag litter lasts for 5 years (0.9 m²a)</td>
<td>Assume to float for 6 months (65 g/year)</td>
</tr>
<tr>
<td>LDPE “bag for life”</td>
<td>42 * 42 cm (0.09 m²)</td>
<td>125.4 g</td>
<td>Assume bag litter lasts for 2 years (0.18 m²a)</td>
<td>Assume to float for 6 months (62 g/year)</td>
</tr>
<tr>
<td>Calico bag</td>
<td>42*42 cm (0.09 m²)</td>
<td>125.4 g</td>
<td>Assume bag litter lasts for 2 years (0.18 m²a)</td>
<td>Sinks in 1 day (0.34 g/year)</td>
</tr>
</tbody>
</table>

### 6.6.1 Greenhouse comparison between the degradable polymers and alternative materials

Figure 12 illustrates the greenhouse gas emission profile for the six degradable polymers compared with six alternative materials – two single-use materials (i.e., HDPE and Kraft paper) and four reusable materials (i.e., calico, PP fibre “green bag”, woven HDPE “swag bag” and LDPE “bag for life” bag). The findings in this streamlined LCA related to greenhouse indicate that reusable bags still have a lower impact upon the environment, than HDPE singlet bags or degradable polymers. Greenhouse impacts are dominated by carbon dioxide through electricity and fuels consumption, methane emissions through degradation of materials in anaerobic conditions (e.g., landfill) and nitrous oxide (N₂O) emissions in fertilizer applications on crops (Figure 12). Degradable polymers with starch content have higher impacts upon greenhouse due to methane emissions during landfill degradation and N₂O emissions from fertilizing crops.
6.6.2 Resource (abiotic) depletion

Resource (abiotic) depletion refers to the consumption of non-living resources (e.g., coal, oil, gas). As most of the degradable polymers are based upon 50% starch their dependence upon fossil fuels as material feedstocks is reduced (Figure 13). The Kraft paper is high in this category due to the consumption of electricity and gas in paper production.
6.6.3 Eutrophication

Eutrophication refers to the emissions of nitrates and phosphates into waterways. As Figure 14 indicates those materials from renewable resources (e.g., crops) have impacts upon eutrophication due to the application of fertilizers to land.
6.6.4 Litter categories

Two litter measurements were modeled in the streamlined LCA to provide some indication of the behaviour of the different materials as litter aesthetics and litter marine biodiversity (which refers to the potential for litter being ingested or entangled with marine fauna.). Table 11 and Table 15 list the assumptions and values used in modelling the litter categories for each bag and Figure 15 graphically presents the different bag materials in the two litter categories. The single-use bags have higher litter values due to the higher possibility of them being littered compared with reusable bags. The marine biodiversity category is mostly affected by the propensity of the material to float or sink. Higher impacts are modelled in the marine biodiversity category if the material floats as it is assumed to float for 6 months (3 months for the oxo-biodegradable bag) and if it sinks the material is assumed to take around one day to sink. The values chosen here have been estimated in the absence of definitive data on the subject and are presented to show how the potential marine impact may vary under these assumptions.
6.7 Sensitivity analysis for reuse of kraft paper bags

A sensitivity analysis was performed to determine the effect of reusing kraft paper bags. In the above results it is assumed that the kraft paper bags are single trip bags. In the sensitivity it is assumed that each bag will be reused a second time\(^\text{21}\) (therefore you only need 260 bags compared with 520 bags in one year). Figure 16 illustrates the reduction in greenhouse gases if the kraft paper bag is assumed to be reused a second time.

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\(^{21}\) This is consistent with feedback from Coles Supermarkets that bags appear to be coming back at least once.
6.8 Conclusion

The conclusion that was reached in the earlier study of plastic bags and alternatives Nolan ITU et al (2002) was again supported by this study, i.e. that reusable bags have lower environmental impacts than all of the single-use bags. Degradable bags have similar greenhouse impacts to conventional HDPE bags (apart from Mater-Bi, which is higher), and depending on the source of the raw material may have much higher nutrient impacts (eutrophication) from farming activity. On the other hand the conventional polymers have higher resource impacts (abiotic depletion). If the degradable material can be kept out of landfill, and managed through composting the impacts will be reduced, but not eliminated.

Table 16 provides a comparison of environmental impacts of degradable shopping bags and alternatives.
Table 16: Assessment of alternative packaging systems, based on a household making 52 shopping trips per year

<table>
<thead>
<tr>
<th>Material</th>
<th>Consumption</th>
<th>Greenhouse</th>
<th>Abiotic depletion</th>
<th>Eutrophication</th>
<th>Litter Marine Biodiversity</th>
<th>Litter Aesthetics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>kg</td>
<td>kg CO₂</td>
<td>kg Sb eq</td>
<td>kg PO4 eq</td>
<td>kg.y</td>
<td>m2.y</td>
</tr>
<tr>
<td>Bionelle</td>
<td>3.12</td>
<td>6.29</td>
<td>0.019</td>
<td>0.256</td>
<td>0.043</td>
<td>1.56</td>
</tr>
<tr>
<td>Eco-Flex Bag</td>
<td>3.12</td>
<td>6.17</td>
<td>0.034</td>
<td>0.207</td>
<td>0.043</td>
<td>1.56</td>
</tr>
<tr>
<td>Mater-Bi</td>
<td>4.21</td>
<td>9.41</td>
<td>0.055</td>
<td>0.278</td>
<td>0.057</td>
<td>1.56</td>
</tr>
<tr>
<td>Earthstrength</td>
<td>3.12</td>
<td>6.49</td>
<td>0.072</td>
<td>0.124</td>
<td>7.8</td>
<td>1.56</td>
</tr>
<tr>
<td>Oxo-biodegradable</td>
<td>3.12</td>
<td>6.06</td>
<td>0.095</td>
<td>0.002</td>
<td>3.9</td>
<td>1.56</td>
</tr>
<tr>
<td>PLA</td>
<td>4.212</td>
<td>20.1</td>
<td>0.107</td>
<td>0.83</td>
<td>0.057</td>
<td>1.56</td>
</tr>
<tr>
<td>HDPE</td>
<td>3.12</td>
<td>6.08</td>
<td>0.099</td>
<td>0.002</td>
<td>7.8</td>
<td>6.24</td>
</tr>
<tr>
<td>Kraft Paper - reusable</td>
<td>22.152</td>
<td>30.5</td>
<td>0.273</td>
<td>0.026</td>
<td>0.30</td>
<td>1.56</td>
</tr>
<tr>
<td>PP Fibre - reusable</td>
<td>0.209</td>
<td>1.95</td>
<td>0.022</td>
<td>0.001</td>
<td>0.241</td>
<td>0.037</td>
</tr>
<tr>
<td>Woven HDPE reusable</td>
<td>0.216</td>
<td>0.628</td>
<td>0.009</td>
<td>0.00</td>
<td>0.107</td>
<td>0.029</td>
</tr>
<tr>
<td>Calico - reusable</td>
<td>1.141</td>
<td>2.56</td>
<td>0.059</td>
<td>0.01</td>
<td>0.003</td>
<td>0.03</td>
</tr>
<tr>
<td>LDPE reusable</td>
<td>1.04</td>
<td>2.72</td>
<td>0.041</td>
<td>0.001</td>
<td>2.571</td>
<td>0.149</td>
</tr>
</tbody>
</table>
7 Summary of conclusions and recommendations

7.1 Degradable polymers
Degradable bags can be classified in two ways:

- According to the way that they degrade, for example whether they are biodegradable, oxo-biodegradable, photodegradable or water soluble; and

- According to the materials they are manufactured from, for example whether they are made directly from renewable starch, indirectly from the fermentation of renewable carbohydrates, from synthetic polyesters or from a blend of a either polyester or polyethylene with an additive to facilitate degradation.

It is very important to understand that these polymers are designed to degrade in different ways and in different environments. The following definitions are useful:

- Biodegradable - capable of undergoing decomposition into carbon dioxide, methane, water, inorganic compounds, or biomass in which the predominant mechanism is the enzymatic action of microorganisms (bacteria, fungi, algae).

- Compostable - degradable under composting conditions, i.e. must break down under the action of microorganisms, achieve total mineralization (conversion into carbon dioxide, methane, water, inorganic compounds or biomass under aerobic conditions) and the mineralization rate must be high and compatible with the composting process.

- Oxo-biodegradable - controlled degradation through the incorporation of prodegradant additive masterbatches or concentrates, which allows polymers to oxidize and embrittle in the environment and erode under the influence of weathering, pressure or agitation.

- Photodegradable - break down through the action of ultraviolet (UV) light, which degrades the chemical bond or link in the polymer or chemical structure of the plastic.

- Water-soluble - dissolve in water within a designated temperature range and then biodegrade in contact with microorganisms.

While the potential list of degradable polymer types is extensive there are certain degradable plastic systems that are preferred for the manufacture of plastic bags on the basis of their favorable property profile. The material must perform in a similar way to conventional polymers, and must be capable of being processed on conventional film manufacturing equipment. It must also remain stable (i.e. not degrade) until it has reached the end of its useful life.

The following degradable plastic materials are suitable for bag applications and are therefore the focus of this study:

- Starch-polyester blends including:
  - Starch with polycaprolactone (PCL) (e.g., Mater-Bi™);
  - Starch with polybutylene adipate terephthalate (PBAT) (e.g., Ecoflex); and
- Starch with polybutylene succinate/adipate (PBS/A) (e.g., Bionelle™).
- Starch-polyethylene blends (e.g. Earthstrength)
- Polyethylene (PE) with a prodegradant (e.g. TDPA™)
- Polylactic acid (PLA).

Much of the analysis in this report focuses on these polymer groups. It is assumed that the starch-based polymers will all be used in polyester or polyethylene blends for a couple of reasons:

- **Performance** – too much starch polymer makes it more difficult to meet performance requirements (e.g. strength) (a 50/50 blend is not uncommon); and
- **Cost** – polyester resins tend to be expensive and cost prohibitive in these types of applications unless blended with lower cost starch resins.

### 7.2 Environmental impacts at end of life

The impacts of degradable polymers at end-of-life depend on the characteristics of the polymer itself (i.e. what the polymer is made from and how it is designed to degrade), the thickness and surface area of the product, as well as the disposal environment. The main disposal environments considered relevant to Australia, and issues relevant to the introduction of degradable polymers are provided in Table 17 below.
Table 17 Disposal options and issues

<table>
<thead>
<tr>
<th>Disposal environment</th>
<th>Issues for degradable polymers</th>
</tr>
</thead>
<tbody>
<tr>
<td>'Dry tomb' landfills (conventional landfill with lining, leachate recovery, gas</td>
<td>Designed to minimise degradation through compaction and leachate recovery. The degradation process is very slow beneath the surface once buried and compacted.</td>
</tr>
<tr>
<td>recovery, daily compaction and daily cover)</td>
<td></td>
</tr>
<tr>
<td>'Wet' biodigester landfills (trial landfills with re-circulation of leachate to</td>
<td>Marginally faster degradation than dry landfills due to increased heat and moisture, but unlike composting processes, the waste is not shredded first.</td>
</tr>
<tr>
<td>promote degradation and biogas recovery)</td>
<td></td>
</tr>
<tr>
<td>Commercial composting (enclosed, open windrow or a combination)</td>
<td>Organic waste is shredded and turned regularly to promote aerobic composting through the action of bacteria, fungi and other microorganisms. Microorganisms require oxygen, water, food (carbon, nitrogen etc) and heat. The ASTM Standard requires 60% mineralization of degradable polymers within 180 days, but this means that the hydrocarbon component of a mixed polymer is potentially left in the compost. The quality of the end compost is critical to commercial markets. The European Standard requires 90% mineralization.</td>
</tr>
<tr>
<td>Enclosed anaerobic digestion with recovery of biogas</td>
<td>Processing of organic material in a digester (i.e. in the absence of oxygen) and generation of biogas, which is converted to electricity. Degradation occurs as a result of microbial attack.</td>
</tr>
<tr>
<td>Home composting (open or enclosed household systems)</td>
<td>There are a variety of open and closed systems for home composting. Degradation tends to be slower due to the uncontrolled conditions.</td>
</tr>
<tr>
<td>Land-based litter</td>
<td>Litter is exposed to heat and light but not to microorganisms.</td>
</tr>
<tr>
<td>Freshwater litter</td>
<td>Litter is exposed to water and microorganisms, as well as heat and light on the surface of the water. Products that float have a greater visual impact and are more likely to be ingested by fish and marine mammals.</td>
</tr>
<tr>
<td>Marine litter</td>
<td>Litter is exposed to water as well as heat and light on the surface of the water as well as microbial digestion.</td>
</tr>
</tbody>
</table>

Based on an extensive literature review and industry interviews, the following conclusions can be drawn about each of the main polymer groups listed above.
Starch – polyester blends

These polymers are biodegradable, which means they degrade due to the actions of microorganisms such as bacteria, fungi, algae and starch digesting enzymes (amylase). Both the starch and the polyester components are naturally degradable. Starch – polyester blends meet the ASTM Standard for compostable plastics, which means that they break down to carbon dioxide (CO$_2$), water, inorganic compounds and biomass within an acceptable time period. They will fully degrade in composting and anaerobic digestion facilities. Degradation will also occur in landfills but at a slower rate.

Starch – polyester blends will disintegrate in the litter stream if they come into contact with water but will not biodegrade without the presence of microorganisms. They have an advantage in marine and freshwater litter because they have a density greater than one, and will therefore sink. This makes them less visible and less likely to be ingested by fish or marine mammals.

Starch - polyethylene (PE) blends

The starch component of these polymers will degrade in a similar way to the starch – polyester blends, but degradation behaviour will depend on the amount of starch included in the blend. Unlike polyesters, polyethylene is not naturally degradable. Some products currently on the Australian market are labeled ‘totally degradable’ but are believed to contain only around 30% starch to 70% polyethylene. While the starch is degradable, the encapsulation of starch in polyethylene will inhibit ingestion by microorganisms.

Polyethylene with a prodegradant additive

Many products currently available on the Australian market, including shopping bags, garbage bags and kitchen tidy bags are made from polyethylene with small amounts (around 3%) of a prodegradant additive. Degradation of these polymers occurs in two stages: the molecules disintegrate through oxidation, and the small molecules then biodegrade through ingestion by microorganisms. These polymers degrade in landfill and in composting facilities, but do not meet the ASTM Standard for compostable plastics, as they take longer than 180 days to reach 60% mineralization. This means that fragments of the plastic may still be visible (e.g. for brightly coloured plastic). While this does not have any environmental risk (the plastic acts as humus in the compost and therefore has a positive impact) it does have a potential visual impact. The market for compost from recycled organics is highly sensitive to the presence of contamination with plastics and other non-organic fractions.

The ASTM Composting Standard is currently being revised, and the new Standard to be released on November 2003 will, according to one of the manufacturers, allow polymers to be oxidized before testing for compliance and this will allow the PE – prodegradant polymers to possibly meet the Standard.

If these products end up in the litter stream they will degrade (disintegrate) but not biodegrade, which means that small fragments of plastic will remain in the environment for an extended period of time. While polyethylene floats (has a density less than 1), the prodegradant additives appear to change the
density and give neutral buoyancy in water (particles neither sink nor float on the surface), inferring a
density of around 1\textsuperscript{22}. This may increase the potential risk of ingestion by fish and marine mammals.

Some prodegradant additives are based on transition metal ions (Mn, Cu, Fe, Co, Ni, Ce\textsuperscript{23}) and metal complexes (e.g. cobalt stearate, cerium stearate). While some research on degradable plastic mulch films has found the impacts of nickel on plants to be insignificant, the potential impacts of prodegradants on the environment are generally not well understood and require further study.

**Polyactic acid (PLA)**

PLA is a biodegradable synthetic polymer made from hydrocarbons, and one of the most commonly used degradable polymers. Like the starch–polyester blends, it is biodegradable and compostable. It will fully degrade in composting and anaerobic digestion facilities. Degradation will also occur in landfills but at a slower rate. They also behave in a similar way in the litter stream, i.e. they will disintegrate on land in contact with water (but not necessarily biodegrade) but will be more likely to sink and biodegrade in waterways.

**Time taken to degrade**

The time taken to degrade in different disposal environments is critical in reaching any conclusions about potential environmental impacts and benefits. Table 3 summarized the available knowledge (some of it supplied by manufacturers), on degradation times, although in some cases available research data is limited and it depends very much on environmental conditions (e.g. climate) and thickness of the product.

**7.3 Environmental impacts over the total life cycle**

A streamlined Life Cycle Assessment (LCA) was undertaken for bags manufactured from degradable polymers. These were compared to conventional high density polyethylene (HDPE) bags, paper bags, reusable plastic bags and calico bags.

The conclusion that was reached in the earlier study of plastic bags and alternatives (Nolan ITU et al. 2002) was again supported by the LCA undertaken for this study, i.e. that reusable bags have lower environmental impacts than all of the single-use bags, including both conventional HDPE bags and degradable bags.

Degradable bags have increased impacts in some impact categories, for example:

- **Greenhouse** - *degradable polymers with starch content have higher impacts upon greenhouse* due to methane emissions during landfill degradation and N\textsubscript{2}O emissions from fertilizing crops.

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\textsuperscript{22} This was found to be the case in a basic test performed by the research team, but would need to be tested scientifically to accurately determine density.

\textsuperscript{23} Mn = manganese, Cu = copper, Fe = iron, Co – cobalt, Ni = nickel and Ce = cerium
- Eutrophication (emissions of nitrates and phosphates into waterways) – degradable polymers manufactured from renewable resources (e.g., crops) have greater impacts upon eutrophication due to the application of fertilizers to land.

The benefits of degradable bags are in lower consumption of non-renewable resources and faster rates of degradation in the litter stream (with potential benefits for wildlife is less plastics are ingested by fish and marine mammals).

7.4 Degradable plastic in litter

Plastic bags have been estimated to make up around 2% of litter items, but this low figure does not reflect their full impact. They have disproportionate visual impacts because they are lightweight, which means they float and get caught in vegetation, and they are a potential threat to wildlife. Plastic bags have been found ingested by sea turtles, which are threatened species.

Degradable polymers could potentially reduce the visual impacts of plastic bags in the litter stream. On land the bags will disintegrate relatively quickly if exposed to heat, UV light, mechanical stress and/or water, but will take a long time to biodegrade in the absence of microorganisms. The likely impacts on wildlife are not clear.

Litter organisations contacted for this study were strongly opposed to the introduction of degradable bags as a solution to the litter problem. While it was agreed that the use of degradable polymers in some applications could be useful in addressing marine litter issues, again it was felt that this would send the wrong message to the consumer and result in a higher level of marine litter. At this stage these views are not supported by any independent research and will need to be evaluated through further research.

7.5 Potential impacts on Australian industry

For the purpose of this report, plastic bags were defined as supermarket and retail shopping bags, green waste / compost bags, bin liners, fruit bags / mesh, bait bags, dog faeces collection bags, bread and ice bags; with the main focus on shopping carry bags.

Based on industry information, approximately 10.5 billion of these bags are consumed in Australia each year. The largest component is retail carry-bags (6.9 billion), of which around 60% are imported.

Companies that may be affected by the introduction of degradable bags into the Australian include polymer suppliers and bag manufacturers. Some of the bag manufacturers already manufacture degradable bags using starch-based polymers or prodegradant additives, and all would have potential to supply degradable bags to meet market demand if required. Degradable polymers can be processed on conventional film blowing lines with only minor modifications.

There are a range of different degradable polymer bags already on the market in Australia, including:

24 Victorian Litter Action Alliance, Clean Up Australia, EcoRecycle Victoria, Melbourne Water, Keep Australia Beautiful Victoria
• Oxo-biodegradable shopping bags, garbage bags and kitchen tidy bags (polyethylene and a prodegradant additive); and

• Biodegradable garbage bags, kitchen tidy bags, bait bags and dog faeces bags (starch – polyester or starch – polyethylene blends).

The oxo-biodegradable bags (polyethylene with prodegradant additives) and some biodegradable bags are manufactured in Australia, while others are imported. While current consumption of degradable bags is relatively small, many new film and bags applications are emerging in Australia. Any growth in demand for prodegradant bags could be met by existing Australian bag manufacturers with very little impact on resin suppliers (the additives are normally added at a rate of around 3%).

While there is one local manufacturer of starch-based polymer bags, Earthstrength tapioca starch bags are imported from Malaysia, and some of the Mater-Bi bags are imported from Italy. While Australia has a strong agricultural sector that could potentially supply tapioca, corn or other crops for the manufacture of starch, the likelihood of a new polymer manufacturing industry being established in Australia is low. The Australian polymer industry has been undergoing a process of rationalization and downsizing for many years in the face of heavy competition from lower cost suppliers overseas.

7.6 Potential impacts on recycling

Many plastics recyclers fear that degradable products and their additives will contaminate batches of recycled resins.

Environmentally degradable plastics by their very nature are designed to breakdown under the influence of heat, light, moisture, pressure and/or agitation. Given this, degradable plastics have the potential to interfere with the processing of recovered polymers and to destabilize and compromise the properties of recycled polymers if they enter the plastics recycling stream. In particular, prodegradant type degradable plastics may cause catalytic or sensitized degradation of recyclable commodity plastics. The consequential effect of this may be premature failure or a reduction of the structural integrity of recycled plastic pipe, plastic bins and crates and film/sheeting products.

Manufacturers of prodegradant additives claim that their product does not have a negative impact on recycling due to the small amount used, and the ‘dilution affects’ once the bags are mixed with other film and bag products.

There is a need for further research on the impacts of degradable polymers, particularly the prodegradant additives, on recycling. Current assurances provided by manufacturers may be correct, but they need to be independently tested and verified. At this stage, a precautionary approach would seem to justify the removal of degradable bags from recycling to avoid the potential for product failure.

25 Degradable plastics can in theory be kept out of the recycling stream, through colour coding of degradable bags and education. In practice it would be difficult to achieve if degradable and non-degradable bags are both used in the same community.
The revised Code of Practice for Shopping Bags is likely to include a 15% recycling target for HDPE shopping bags if collection is only from the supermarkets themselves, and 30% if bags are also collected from kerbside. The choice for retailers and bag manufacturers appears to be either to pursue a recycling strategy or a composting strategy for the bags – not both. Degradable bags have potential to reduce the quality of recyclate from plastic bags and to therefore undermine plastics recycling programs.

7.7 Potential impacts on consumers

The convenience of conventional plastic bags, particularly shopping bags, is an important issue in looking for environmentally preferred solutions. One of the benefits of degradable bags is that they do not require consumers to change their habits, i.e. they still have access to the same style of bag, free of charge, every time they go to the supermarket. Unlike reusable alternatives such as calico or heavy plastic bags, they do not need to remember to bring bags each time they shop.

Plastic bags are also convenient in the home for reuse as bin liners, rubbish bags and a multitude of other purposes. The replacement of conventional bags with degradable bags will not prevent consumers reusing them at home as they will not break down until exposed to the required conditions, e.g. heat and light or microorganisms in the soil.

The consumer focus group held as part of this study, and feedback from Ritchies Supermarkets, indicates that degradable bags are a popular choice among consumers. They are seen as an environmentally preferred option that helps to alleviate feelings of guilt about excessive bag use. When combined with positive environmental messages on the bag itself or in other store communications, they also have potential to encourage more responsible consumer behaviour in other areas.

7.8 Recommended applications for degradable bags

Biodegradable plastics have beneficial uses where the biodegradable plastic alternative has been shown through to achieve the following:

- Meets the overall needs of the application with additional technical and potential environmental benefits;
- Reduces labor or energy required to manage solids (e.g. composting facilities); and/or
- Reduces other environmental and social impacts associated with other conventional products, e.g. by reducing litter.

With the development of various biodegradable plastics with differing structures, properties and degradation behaviors, a range of potentially suitable application areas are emerging. Appropriate applications for degradable polymers are dependent on both the performance requirements of the product (strength, contents, length of time package needs to remain stable before degradation etc) and the likely or intended disposal environment.

Biodegradable plastics including starch based polymers and polyesters, are designed to break down under composting conditions, i.e. through the actions of microorganisms. This makes them ideally...
suited to products that will be collected as part of a source-separated organics collection, e.g. green and food waste bags collected from households. Given that the trend internationally and in Australia is to increase diversion of organic wastes (food, green waste and timber) from landfill to commercial organics recovery facilities, there are good opportunities for replacement of conventional polymers with biodegradable polymers in these applications. Dog faeces bags provided in public areas may also be appropriate if they are likely to be collected for disposal in an organics recovery facility.

Oxo-biodegradable polymers (with prodegradant additives) are designed to break down under the influence of heat and UV light. Final biodegradation takes place through the action of microorganisms, although there still appears to be some uncertainty about the time needed to fully degrade (particularly whether it can occur within the normal commercial composting period) and the environmental impacts of prodegradant additives based on metals such as cobalt.

The advantages of degradable polymers in landfill are questionable. Minimal degradation of organic materials (including food and green waste) takes place in controlled dry landfills. In wet landfills degradation is more likely to take place, and degradation of organic materials could have negative impacts on greenhouse gas generation and contamination of groundwater with leachate if they are not well controlled. The use of biodegradable or oxo-biodegradable polymers for products that are designed for disposal in landfill will result in a loss of resources as the products will not be recovered through either composting or recycling, and will have very little impact on the quantity of waste to landfill or the life of landfills.

Degradable polymers will change the nature of litter, because products made from biodegradable or oxo-biodegradable polymers will break down to some extent in contact with UV light and water into smaller pieces. In these circumstances they will therefore be less visible and have a lower risk of ingestion by larger fish or marine mammals. However, they may pose a greater risk to smaller animals such as sea turtle hatchlings. Environmental conditions in the litter stream are not ideal for biodegradation, however, as they are uncontrolled and polymers may not come into contact with microorganisms. Once again there is uncertainty about the time any product will take to completely biodegrade, and whether partially degraded products still pose a risk to wildlife.

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26 Modern wet landfills collect biogas (methane) for energy generation after the landfill has been capped and closed. Gases escape to the atmosphere while it is being filled (before capping); a small percentage escapes even while gas is being collected; and some gas continues to be generated after the gas recovery system has been decommissioned. If gas recovery could be improved over the total life cycle of the landfill then degradable bags would have less impact on greenhouse gas generation.

27 Shopping bags only make up around 2.5% of total plastics, or 1% of total packaging, consumed in Australia each year. Even if all bags were made from 100% degradable resins they are unlikely to biodegrade completely in landfill due to the less than ideal conditions. The overall impact will therefore be minimal.
Biodegradable polymers are expected to break down faster than oxo-biodegradable polymers in marine and fresh water, and may therefore be appropriate for products that are likely to be littered in these environments. Bait bags are a good example of this.

While the use of degradable bags for retail shopping bags may reduce the visual impact of bags in litter, its use in this application is problematic for several other reasons:

- Plastic bags are collected for recycling in the two major supermarket chains and a number of Councils are undertaking or planning kerbside collection of the bags. Degradable bags reduce the quality of the recyclate and for some products increase the risk of product failure.
- Retail shopping bags are unlikely to end up in a composting environment and the benefit of degradation in landfills is marginal.
- Over their total life cycle, degradable bags have a greater impact on the environment than conventional HDPE or LDPE bags in a number of areas, including greenhouse emissions and eutrophication.

They may however be an argument for using degradable polymers for shopping bags (and other applications) in remote areas and islands that do not have access to recycling systems, and where bags are a significant contributor to the litter stream. This would need to be carefully managed by Councils and/or retailers to ensure that all bags were degradable and managed appropriately.

### 7.9 An integrated approach to the introduction of degradable bags

The introduction of degradable bags in the Australian market needs to be carefully managed to ensure that it results in positive environmental, social and economic outcomes. An integrated approach that includes the following elements is needed:

- Design for environment – a life cycle management approach that involves selection of appropriate polymers (degradable or otherwise) for each specific application, avoidance of potentially toxic additives, appropriate colour-coding or labeling to identify degradability, and design of appropriate recovery or disposal systems.
- An Australian Standard to control the use of degradable polymers and to allow independent verification of manufacturers’ claims.
- Consumer education including accurate labeling of biodegradable, compostable and oxo-biodegradable polymers.

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28 For example, Mater-Bi bags produce approximately 50% more greenhouse gases (kg/CO2 equivalent) over their total life cycle than conventional HDPE bags. PLA bags produce around 200% more (see section 6.6.1 and Table 16).
7.9.1 Design for Environment

‘Design for Environment’ (DFE) is a generic term for measures taken to design products that have reduced impact on the environment. In the case of degradable plastics there are several options for DFE strategies:

- Design of new polymers or polymer blends that meet requirements for performance, degradability and cost;
- Specification of appropriate degradable polymers for film products such as bags;
- Design of bags to minimize potential problems such as contamination of recycling or composting streams; and
- Design of appropriate life cycle management strategies, including end-of-life recovery systems to ensure that products actually degrade.

Australian research organizations could contribute to the development of new degradable polymers. Plactic was developed by the CRC for Packaging with input from CSIRO and Swinburne University. CSIRO is interested in undertaking further work in this field (Wu 2003).

There is a lot of confusion and misinformation in the market about the types of degradable polymers and their benefits. A basic information kit needs to be prepared to inform buyers and manufacturers about the different polymers and appropriate life cycle management strategies.

Design of products also needs to consider other issues to minimize impacts at end-of-life, such as the avoidance of metal-based additives, e.g. copper in pigments (green colours).

Feedback from commercial composters has suggested that degradable plastics could be a unique colour (possibly bright green) so they can be easily differentiated from non-degradable plastics in a composting environment. This way non-degradable plastics can still be manually removed and the degradable plastics can be left in situ. A colour coding system could be investigated as a means of identifying degradable plastic types. The costs and benefits of introducing a unique colour-based identification of degradable plastics to also assist plastic recyclers in identifying those plastics that are not compatible with their mechanical recycling processes could also be investigated. This would need to be managed through a voluntary mechanism such as a Code of Practice.

In other areas there is an opportunity to investigate strategies that mimic nature’s own mechanisms – for example many marine creatures may choose red, through an evolutionary process, to elude predators. Water absorbs light energy, the longest wavelengths to go first: red, followed by orange, yellow, green, blue, indigo, and violet. Thus red offers good camouflage and maybe a sensible choice for a degradable ‘bait’ bag.

Also to decrease the desirability of degradable plastics and their breakdown fragments to terrestrial animals the additive Bitrex (denatonium benzoate) can be incorporated into the formulation. Bitrex is an extremely bitter but safe additive that can be detected by animals at just 50 parts per billion. A bitter taste is nature’s own warning signal since many poisonous plants contain bitter alkaloids.
Density adjustment via the incorporation of inert mineral fillers can also help by causing plastic bags to sink in aquatic environments thereby decreasing their visibility to turtles and dolphins.

### 7.9.2 Australian Standard

A number of degradable plastic types that are presently being imported into Australia are purported to be degradable plastics but are simply polyethylene-starch blends or even simply polyethylene. Since the range of degradable polymer options is expected to increase in coming years there is a pressing need to develop an Australia Standard for degradable plastics.

This standard will serve as a reference point for all Australian producers, importers, buyers, authorities, facility managers and consumers. It is currently difficult to verify whether polymers comply with relevant overseas standards other than by conducting expensive testing. It is also important to recognise that the extent of degradation depends on the thickness of the product, for example degradable plastic cutlery will take longer to degrade than thin plastic film.

An Australian Standard for degradable plastics should address the following areas:

- Provision of test methods that enables both the biodegradation and oxo-biodegradation of the degradable plastic to be validated;
- A system for certification of degradable polymers that conform to the standard (e.g. the system used for EN 13432);
- The standard should give coverage to the range of potential application areas and disposal environments in Australia;
- The standard should not be so severe as to exclude Kraft paper as do some European standards;
- The standard should be developed with reference to the existing international standards. The standard should differentiate between biodegradable and other degradable plastics (as does ASTM D6400);
- Clarification between biodegradation and abiotic disintegration even if both systems demonstrate that sufficient disintegration of the plastic has been achieved within the specified testing time;
- The standard should address environmental fate and toxicity issues (as does ASTM D5152);
- The standard should sensibly answer the debate on whether total mineralization is required (i.e. the conversion into CO₂, H₂O, inorganic compounds and biomass under aerobic conditions) or whether disintegration (into fine visually indistinguishable fragments) and partial mineralization that is compatible with the composting process is adequate.

A range of international standards and test methods has been developed specifically for degradable plastics. A family of ASTM standards addresses physical property deterioration in a variety of specific environmental conditions including simulated composting (D5509, D5512), simulated landfill (D5525),
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Aerobic microbial activity (D5247) and marine floating conditions (D5437). A second group of ASTM standards addresses CO₂ generation in aerobic environments including sewage sludge (D5209), activated sewage sludge (D5271), and controlled composting (D5338). A third group of ASTM standards addresses CH4/CO₂ evolution in anaerobic environments such as anaerobic sewage sludge (D5210), anaerobic biodegradation (D5511), and accelerated landfill (D5526). In addition, three International Standards Organisation (ISO) standards have set the criteria by which European degradable 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).

The proposed Australian standard should treat cellulose (e.g. garden waste or paper) as a benchmark material and degradable plastics should achieve comparable rates of degradation to cellulosics within certain tolerances. Important consideration should be given the 60% mineralization criteria (used by the DIN and ASTM standards) since it may provide a loophole for certain degradable plastics. For example, if a plastic is comprised of two components, say 60% A and 40% B, where A is degradable and B is recalcitrant, a 60% degradation may mean a 100% biodegradation of one component but a 0% degradation of the other. The CEN standard for example requires 90% degradation.

The standard should consider what are optimum conditions for composting for organics and not the degradable plastics themselves. For example, the standard composting temperature has been raised by various standards committees overseas to 58°C in order for PLA to give better results.

However, better compost quality is achieved if the composting is performed at temperatures lower than 55°C. For prodegradant type degradable plastics a screening test should be incorporated into the standard that involves exposure in a QUV apparatus followed by measurement of mechanical properties or carbonyl index.

The standard must not only assess degradability potential but should also assess whether the degradable plastic materials have a negative effect on compost or soil quality. This involves chemical analyses (e.g. heavy metals assay) as well as ecotoxicity tests such as plant germination tests and earthworm toxicity tests. The purpose of these tests is to make sure that residues and additives from the plastics do not have an adverse effect on compost or soil quality (i.e. are not toxic and do not deter plant growth). For example in terms of heavy metal content the Europeans have adopted the protocol that the material must not exceed a heavy metals content above 50% of that for normal compost.

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 the proposed standard should include plant phytotoxicity testing on the finished compost that contains degraded polymers.

The standard should reflect the unique set of conditions and climates that Australia presents. For example, climatic differences between Australia and Europe/North America such as higher iloLangleys (i.e. higher irradiance) and lower average rainfall. The proposed standard should address the
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correlation between bench-scale, lab-scale and full-scale testing of environmentally degradable plastics.

The proposed standard should outline the certification processes for degradable plastic bags which gives a seal of approval (possibly a logo) for bags that pass the relevant tests in the proposed standard. The standard should also address the issue that degradable plastic must be recognizable as degradable or compostable.

Further preparatory information required for development of Australian Standard for degradable plastics include:

- Listing and review of all current overseas standards for degradable plastics (including those in preparation)

- Due consideration should be given to alternative natural materials such as paper and jute. In Europe and US such natural materials if they are not chemically modified do not have to pass the standards. In some cases these natural materials do not break down as required by the standard for degradable plastics.

- Presently overseas standards and test methods for degradable polymers focus heavily on composting however the standards should reflect better the ultimate disposal environment. That is, if 80% of degradable plastics end up in landfills and 10% in marine environments then the standards need to place proportional emphasis on these disposal environments.

- The standards should also consider the fate of degradable materials with respect to actual disposal environments and not assume that these are limited to composting, landfilling and marine environments. Other disposal environments include marine floating conditions, marine sinking conditions, sweet water, sewage treatment, sewage sludge, activated sewage sludge, controlled anaerobic sewage sludge, anaerobic biodegradation, dry desert soil.

- Standards should also consider the fact that degradation rates are highly dependent on the thickness and geometry of the fabricated articles. While impressive breakdown rates are often quoted (e.g. 6-8 weeks) these generally applied for thin films. Thick-walled articles such as plates, food trays and cutlery can takes 6 months to a year to biologically degrade. Therefore any quoted biodegradation rates should specify the mean thickness and shape of the fabricated article as well as the disposal environment and ideally the species of microorganism.

- The standards should consider that laboratory scale test methods may give an underestimation of the biodegradation rates since they present to small an ecosystem with only a few links from the food chain present.

- The new standard should review the notion that all degradable plastics should degrade almost completely to carbon dioxide since there are many natural packaging materials (e.g. egg shell) for which this does not occur.
The test methods should not just focus on degradability but also on renewability and sustainability. An important question is should the proposed standard favour degradable plastics made from renewable resources (e.g. thermoplastic starch and PLA)?

All the above information and data will help to build a robust testing standard. A proposed protocol for development of the Standard is provided in Figure 17.

Another useful process for taking the issue forward could be to set up a covenant framework for the introduction of degradable plastics into Australia. This could be used to initiate a dialogue between the key players (manufacturers, retailers, governments, and consumers) on the issue of how to introduce degradable plastics into Australia to maximise environmental benefits across all sectors.

**Figure 17 Standards Development Protocol** (Narayan and Pettigrew 1999: 40)

![Figure 17 Standards Development Protocol](image)

### 7.9.3 Consumer education

Labelling of degradable products needs to be accurate and not mislead consumers. The Trade Practices Act prohibits a corporation from engaging in conduct that is misleading or deceptive, or likely to mislead or deceive. There is also an Australian Standard designed to control environmental claims – *Environmental labels and declarations – self declared environmental claims* (AS/NZS ISO 14021:2000).

Given the lack of available information on degradation rates of some polymers, claims such as “100% degradable” could be regarded as potentially misleading. The introduction of an Australian Standard for degradable polymers and a certification scheme will provide an independent and transparent system for evaluating manufacturers’ claims. Labeling of products that are certified to the standard will
provide manufacturers and consumers with a greater level of confidence in the environmental benefits of degradable polymers.

The Biodegradable Products Institute (BPI) in the US, in conjunction with the US Composting Council, has a scheme to certify and promote products that meet ASTM D6400-99 "Specification for Compostable Plastics". Certified products are identified with a logo. There may be potential to explore this option if a standard and certification scheme are established in Australia.
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Yellow Pages Online.  www.yellowpages.com.au
APPENDIX 1: 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).

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 Copolymers

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

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 CO₂ 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 1-4 linked α-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 biodegradation 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”

**Oxo-biodegradable**

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. The remaining fragments are of a low enough molecular weight so that microbes can then assimilate them.

**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 CO₂, H₂O, 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.

**Dry landfill**

A ‘dry’ landfill is designed to minimize the risk of contaminating groundwater by collecting and removing leachate. This is the most common approach to landfill management.

**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.

**Glucosidic linkages**

The ether bonds that hold the glucose units together in the structure of starch. These linkages are readily cleaved by bacteria and enzymes.

**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.

**Hydroperoxidation**

The stage in the oxidation process of polymer where hydroperoxide groups are formed.

**Hydrobiodegradable**
The term used to describe polymers that first degrade by hydrolysis and then by biological attack (e.g. modified PET; Biomax). In the first instance hydrolytic scission of ester bonds occurs then subsequently the smaller fragments are biodegradable.

**Hydrophilic**

Polar polymers that have an affinity for moisture/water (e.g. polyesters).

**Hydrophobic**

Non-polar polymers that have a low affinity for moisture/water (e.g. polyethylene).

**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$_2$O, 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.

**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 (i.e. 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.

**Oxobiodegradable**

The term used to describe polymers that first degrade by oxidation and then the smaller fragments of substantially reduced molecular weight are bioassimilatable (e.g. EPI type PE films). In the first instance oxidative bonds of backbone chain bonds occurs then subsequently the smaller low molecular weight fragments (i.e. waxes) are biodegradable.

**Oxidation Degradation**

The process whereby polymers undergo degradation due to exposure to heat and/or light and oxygen.

**Peroxidation**

The chemical combination of polymers with oxygen (an early stage of the oxidation process)

**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)

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.

Polyolefins
The term used to describe polymers made from alpha-olefins (hydrocarbons with terminal double bonds). Polyethylene and polypropylene are the main polyolefins.

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 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. plasticizers 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.

**Prooxidants**

Additives based on catalytic metal complexes used to make polymers more sensitive to oxidation processes. Such sensitizers are most often based on transition metal compounds containing, for example, stearates of iron, cobalt, nickel and manganese.

**Recalcitrant**

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 plasticized 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 – and able to repeat this process without becoming brittle.

Thermosetting Polymers

Sets firmly and cannot be made plastic again.

Thermoplastic Starch

See Starch Composites (90 % Starch).

Wet landfill

A ‘wet’ landfill is designed to promote bacterial growth and degradation. Leachate is collected, sometimes treated, and pumped back to the top of the landfill, and is therefore continuously recirculating. This type of landfill is not common in Australia.
APPENDIX 2 – Literature review on degradable bags in compost and landfill

Composting seems to be the most promising for waste management options for degradable plastics because the composting process is designed to degrade wastes. There are, however, obstacles that make many communities reluctant to accept plastic bags for composting (Garthe and Kowal 2002).

Large-scale composting operations are well established in many countries, and are an efficient way of producing useful material from what at present is largely garden and agricultural waste. Food wastes may also be used, and this would likely become much more common if inexpensive "one-way " containers were available. Such containers would need to have the low cost and the serviceability of conventional PE bags but, in addition, would need to be compostable. The ASTM definition of compostable is "capable of undergoing biological decomposition in a compost site as part of an available program, such that the material is not visually distinguishable and breaks down into carbon dioxide, water, inorganic compounds, and biomass, at a rate consistent with known compostable materials."

To be convenient for composting, degradable plastic bags should not only break down, but also hold moisture, not be lighter than composting feedstocks and begin to degrade after several days (Chapman 1999).

Ohtaki (2000) examined eight kinds of biodegradable plastics in controlled laboratory composting conditions for their degradability. Ultimate degradability, defined as a molar ratio of carbon loss as CO₂ to the carbon contained in the plastic particles or pellets that have been added to the composting material, was calculated. The ultimate degradability of the biodegradable plastic was found to be dependent strongly on the type of polymer. The degradability of the eight kinds of plastics tested ranged from a small percentage to approximately 65% over the 8-day period of the 50°C composting.

In another study the biodegradability of five different biodegradable garbage bags was analyzed according to the DIN-Standard draft 54'900 “Measurement of the compostability of polymers” (Kaiser 2001). The tests have to prove that a “biodegradable polymer” can be degraded under controlled composting conditions. Five different types of bags were tested. The bags were made from cornstarch, polycaprolactone and kraft paper. To claim compostability the material has to biodegrade and to disintegrate in a composting system, to mineralize completely to carbon dioxide and water, and to fulfill several quality criteria such as a limited amount of heavy metals, no toxic organic compounds and no organic non-biodegradable additives. The mineralization experiments showed that all five materials disintegrated during the rotting process in standardized compost and all five tested products also fulfilled the mineralization rate of 60 % within six months (Kaiser 2001).

Mater-Bi™ is a wholly compostable polymer based on a blend of at least 50% starch and the balance a synthetic hydrophillic degradable polyester. Mater-Bi has undergone extensive biodegradation testing to evaluate its suitability for disposal by composting (Booma et al. 1994; Chiellini and Solaro 1996; Piccinini et al. 1996). These studies indicate that Mater-Bi is readily degradable in standard laboratory biodegradation tests, including the semi-continuous activated sludge (SCAS) test for simulating breakdown in municipal waste-water treatment plants and in pilot composting systems.
The degradation rate of Mater-Bi bags depends on the exact formulation used and physical properties of the product. Toxicity tests undertaken with the Mater-Bi bags and composted products have shown that they are non-toxic in the standard animal and plant tests. Using standard composting test systems over 70% breakdown can be achieved for Mater-Bi plastic bags in 40 days, however the time required for 66% weight loss in the standard activated sludge (9SCAS) test system is approximately 3 months.

Biodegradability of poly(beta-propiolactone) (PPL) was tested in a bench scale composting reactor under controlled conditions by Nakasaki (Natasaki 1998). The composting raw mixture was prepared by mixing commercial dog food instead of real organic waste, saw dust as a bulking agent, commercial inoculum sold for acceleration of composting, and PPL in the ratio 10:9:1:10 on dry weight basis. The optimum temperature for degradation was found to be around 40-50°C where approximately 40 wt.% of PPL was decomposed in 8 days.

Chiellini (2003) recently studied the degradation of LDPE containing TDPA™ pro-oxidant additives from EPI Inc. They found that the LDPE-TDPA did undergo ultimate biodegradation (i.e. mineralization) in simulated soil burial but not readily in composting (mature compost) conditions. Oxidatively degraded LDPE-TDPA films were found to undergo biodegradation as mediated by soil microorganisms reaching a mineralization level of about 60% albeit over a relatively long time frame. Chiellini (2003) reports that oxidized LDPE-TDPA film underwent 50-60% biodegradation (as measured by carbon dioxide evolution) over a period of 18 months. They observed only limited biodegradation however of the LDPE-TDPA films in mature compost as opposed to soil burial. This may be due to microbial population requirements for the biodegradation of oxidized fragments. Mature compost and soil differ substantially in this aspect. In particular it is known that fungal activity in mature compost inhibits microorganisms. Chiellini (2003) points out that the completeness of biodegradation of LDPE-TDPA films and the cumulative time for oxidation are still answered questions at this stage.

Bags based on polymers containing substantial amounts of hydrocarbon polymers such as polyolefins are finding it difficult to meet certifying standards such as ISO-16929. Fungal activity in mature compost inhibits microorganisms and this may explain why the oxo-biodegradable films break down faster in soil burial than in mature compost. Further it is believed that soil oxidation processes assist the degradation of the oxo-biodegradable bags more than microbes.

Manufacturers of oxo-biodegradable polyolefins such as EPI view with concern the development of standards for degradable polymers which demand a high level of mineralization as the primary criterion (Billingham et al. 2002). This protocol was originally developed for hydro-biodegradable polymers, which will primarily end up in sewage. For these polymers and in this application, such test methods are entirely acceptable but they are totally inappropriate for compost, litter and agricultural applications (Billingham et al. 2002).

Biodegradability of PEs modified by prodegradant additives has been assessed by a variety of laboratory-scale and field-scale composting tests. Most recently an extensive commercial-scale composting trial of TDPA additives has been carried out in the municipal composting plant of Vienna Neustadt, Austria, directed by Dr B Raninger (Leoben University) (Billingham et al. 2002).
EPI films and bags have been evaluated in a large-scale composting facility that serves a population of about 100,000 people. It typically treats about 10,000 tons of mixed household and green garden waste annually (Billingham et al. 2002). Composting occurs in two stages: an in-vessel, forced aeration “tunnel” process, followed by an outdoor, open-pile windrow composting stage on a paved area with weekly watering and turning. The compost produced is used mainly for landscaping and gardening.

The highly instrumented tunnels in the composting plant hold 90 m³ of waste. In the trials of the material, the input to one of the tunnels contained just over 1 wt% of LDPE bags (10,000 bags) which contained the TDPA additive but were not pre-aged. The compost was examined after the main maturation period (2 weeks in the tunnel), after post-maturation (12 weeks outdoors) and after six months, all according to Austrian National Standard ON S 2200. Test protocols included mass loss, analysis for heavy metals and tests of seed germination and survival of daphnia and earthworms (Billingham et al. 2002).

The results all show that PE films modified by the EPI additives are oxidatively biodegradable under composting conditions, yielding high-quality compost. No toxic effects could be detected on either seed germination or organism survival (Billingham et al. 2002).

Samples of the final compost were subjected to standard eco-toxicity testing. Tests included seed germination and survival of daphnia and earthworms and were carried out according to DIN V 54900-3, ON S 2200 and ON S 2023. All tests showed absolutely no toxic or harmful by-products. Germination rates and plant yields for cress and summer barley on standard compost and compost containing TDPA formulations showed no significant differences between samples. The final conclusion of this testing was that products using PE and TDPA technology meet all requirements to be classified as degradable compostable plastics and the compost end product is fully acceptable as land fertilizer (Billingham et al. 2002).

It has also been demonstrated that undegraded agricultural plastics based on TDPA prodegradants are non-ecotoxic for the environment and meet all international standards (e.g. EC OJL,219,7.8.98 for soil improvers) (Billingham et al. 2002).

Ecotoxicity tests have also been carried out on soils after use of agricultural films containing EPI prodegradant additives. Tests include Daphnia magna immobilization according to ISO 6341, Earthworm, acute toxicity test according to ISO 11268-1, Cress test according to ISTA, and Oat & lentils test according to ISO 11269-2. In all cases the materials were found to be non-toxic (Billingham et al. 2002).

To help identify products in the United States, the Compostable Logo program was set up by BPI and the USCC. The ASTM D6400-99 standard differentiates between biodegradable and degradable plastics — meaning biodegradable plastics are biologically mineralized and consumed by soil microbes, compared to plastics that do not necessarily biologically mineralize completely but disintegrate due to thermal, photochemical or hydrolytic degradation (BioCycle 2002). The logo helps consumers identify which products meet the ASTM standard. To qualify for the logo, verification that the products meet the ASTM D6400-99 standards is done through an independent third-party reviewer.
chosen by the manufacturer. Many products on the market do not meet ASTM D6400-99 standards (BioCycle 2002).

Currently, oxo-biodegradable prodegradant bags do not meet ASTM’s D6400-99 standards, because they degrade through chemical oxidation before the onset of biodegradation and mineralizes at a slower rate than is acceptable. The ASTM has accepted EPI’s proposal for alternative test method development, according to Graham Swift, a member of the ASTM subcommittee for polymers and a consultant to EPI who has been working on alternative test methods to submit to the ASTM (BioCycle 2002).

William Hogan, president of Willow Ridge who produce the PDQ prodegradant additive masterbatches, says the 12-week requirement for full biodegradation laid down in current ASTM composting standards is relevant only when the goal is disposal in an engineered composting facility—very few of which exist in the U.S. Hogan argues that nine months to five years is a meaningful time frame for degradation in most real-world situations (Leaversuch 2002).

The impact of ‘polyethylene dust’ that remains in compost for an unknown time period has been an ongoing question (BioCycle 2002). Polyethylene products used at least ten years ago did not completely break down and remained visible. Today’s products leave a dust, not visible pieces and the virtues of that are debatable. The question is if any dust — prior to completely mineralizing — should be permitted and still pass ASTM tests (BioCycle 2002).

**Residues in composting**

There is currently little evidence to show that recalcitrant polymer residues in the soil are harmful. In fact the contrary appears to be true. 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 fibers demonstrated improved growing rate and root structure development to accelerate sod production (Gallagher, 2001).

Toxic contamination is an issue that must be addressed before degradable plastics will be fully accepted for composting. Many of the additives in plastic material-plasticizers, coloring pigments, stabilizers, and degradation promoters-can contain heavy toxic metals, which can make the entire compost pile unusable (Garthe and Kowal 2002). The analysis of the heavy metal content of five different biodegradable garbage bags showed that the polymers themselves contained very low amounts of heavy metals. However, the printing with green and blue colours with copper pigments was increasing the copper content in all products (Kaiser 2001).

Prodegradants in the oxo-biodegradable plastics (e.g. EPI degradable plastic) include additives based on transition metal complexes (e.g. cobalt stearate, cerium stearate), which render conventional polyethylene susceptible to hydroperoxidation. The critical point is that only trace quantities of Mn, Cu, Fe, Co, Ni and Ce as compounds are added to the polymer and these mirror the trace elements present in most soils.
Soil burial

A number of studies have been performed measuring the rate of degradation of degradable plastic bags when buried in soil. The rate of polymer degradation is very dependent on the polymer type, material thickness and the amount of bacteria present (Biby 2002).

Microorganisms isolated from soil samples were screened for their ability to degrade various biodegradable polyester-based plastics. The most reactive strain, designated as strain TB-13, was selected as the best strain for degrading these plastics. From its phenotypic and genetic characteristics, strain TB-13 was closely related to Paenibacillus amylyticus. It could degrade poly(lactic acid), poly(butylene succinate), poly(butylene succinate-co-adipate), poly(caprolactone) and poly(ethylene succinate) but not poly(hydroxybutylate-co-valerate). However it could not utilize these plastics as sole carbon sources (Teerphatpornchai et al. 2003).

Hoshino et al. (2002) placed five biodegradable plastic bags in soils for 1 year at nineteen sites in Japan. Among the biodegradable plastic specimens (poly-(3-hydroxy-butyrate-valerate) (PHB/V), poly-(epsilon-caprolactone) (PCL), poly-(Butylene succinate) (PBS), poly-(butylene succinate and adipate) (PBSA), and poly-lactide (PLA)) that were placed in soils for 1 year at nineteen sites in Japan, plastic specimens with appreciable biodegradation were studied for the transformation of the chemical structure by FTIR, H-1-NMR, and C-13-NMR. No appreciable differences in the main absorbency-bands of the aromatic groups were recognised by FTIR for any of the plastic specimens tested. However, both H-1-NMR and C-13-NMR analyses suggested that molecular structure of the PHB/V specimens changed after 1 year placement in soils. In contrast, although weight loss, and/or a decrease in tensile strength and elongation were observed after the placement in soils for the PCL, PBS, PBSA and PLA specimens, the analyses of these specimens by FTIR, H-1-NMR did not reveal any changes in their molecular structure.

The biodegradable plastic PHB/HV (copolymer of 3-hydroxybutyrate and 3-hydroxyvalerate) underwent a faster degradation at 30°C than at 52°C in soil under aerobic conditions, while there was no remarkable difference between 30°C and 52°C in the degradation rate of PCL, PBSA and PBS (Nishide et al. 1999).

PHB showed the fastest rate of degradation among the four plastics at 30°C and PBSA the fastest at 52°C degradation of all the four plastics was not observed at both 30°C and 52°C under anaerobic conditions for 50 days (Nishide et al. 1999). Microorganisms on the degrading plastics appeared to be diverse at 30°C, including bacteria and fungi. However, among the several to ca. 10 kinds of bacterial and fungal strains isolated from the degradation sites of each plastic at 30°C, only one or two fungal strains were able to degrade the respective plastics in vitro. The degraders were identified as Mucor sp. (PHB), Paecilomyces sp. (PCL), Aspergillus sp. (PBSA) and Cunninghamella sp. (PBSA). In contrast, only a single type of fungus was observed at the degradation sites of PCL and PBSA at 52°C. The fungus isolated from PCL and PBSA was identified as Thermomyces sp. This study demonstrated that soil temperature and anaerobiosis exerted significant effects on the degradation of the plastics, and that fungi were mainly responsible for the degradation of the plastics in soil (Nishide et al. 1999).
The degradation behaviour of three commercial biodegradable plastics, poly(3-hydroxybutyrate) (PHB), Sky-Green™ (SG), a biodegradable aliphatic polyester made of succinic acid, adipic acid, butanediol and ethylene glycol and Mater-Bi™ (MB), a composite composed of starch based biodegradable polymers were incubated in forest soil, in sandy soil, in activated sludge soil, and in farm soil at 28, 37 and 60°C respectively was studied by Kim et al (2000). Seven PHB degrading fungi, five SG degrading fungi and six MB degrading fungi were isolated by analyzing the microbiological characteristics of the fungi. Biodegradation of all three polymers was most active in the activated sludge soil (Kim et al. 2000).

Both SG and MB showed higher degradability at 28°C than at 37°C. Biodegradability of PHB was highest at 37°C, while degradation of MB occurred reasonably well at 60°C. In the modified Sturm test Penicillium simplicissimum LAR 13 and Paecilomyces farinosus LAR 10 degraded PHB relatively well, while the degradation rate by Aspergillus fumigatus LAR 9 was lower than expected. P. simplicissimum LAR 13 showed the highest degradation rate for SG and A. fumigatus LAR 9 was most effective in degrading MB. Biodegradability of isolated fungi was affected by the incubation temperature. In both the soil burial test and the modified Sturm test the order of the biodegradation rate was PHB>SG>MB (Kim et al. 2000).

Orhan and Buyukgungor (2000) investigated the biodegradation of disposable low-density polyethylene bags containing starch (12%), autoxidizable fatty acid ester and catalytic agents in soil. This work intended to evaluate the capacity of Phanerochaete chrysosporium to enhance polyethylene film biodegradation in soil microcosms. Soil samples inoculated with P. chrysosporium were mixed with LDPE/starch blend films and biological changes of the films and soil were monitored for 6 months.

Professor Guillet at the University of Toronto in Canada demonstrated the mineralisation of oxidised polypropylene and polystyrene in garden soil and forest soil, again using carbon-14 labelled polymers. In addition to mineralisation, which would be expected to release carbon dioxide into the atmosphere, it has been demonstrated that the oxidised polymer can at least partially be directly assimilated by plants. Using carbon-14 labeled polyethylene, which had been oxidatively degraded, they grew amaranth seedlings on soil to which the degraded material was added. After 14 days they found that carbon-14 derived from the polymer was present in the plants.
APPENDIX 3 – Life cycle assessment

This section reports the streamlined life cycle assessment (LCA) of degradable plastics used in the production of shopping bags. In Nolan ITU et al (2002) a streamlined LCA was conducted for ten shopping bags\(^{29}\). The degradable plastic materials that are suitable for applications in film blowing for shopping bags and/or are current available on the market that will be investigated in the current study are:

- Starch-polyester blends including:
  - Starch with Polycaprolactone (PCL) (e.g., Mater-Bi\(^{\text{TM}}\));
  - Starch with Polybutylene adipate terephthalate (PBAT) (e.g., Ecoflex); and
  - Starch with Polybutylene succinate/adipate (PBS/A) (e.g., Bionelle\(^{\text{TM}}\)).

- Starch-polyethylene blends (e.g. Earthstrength)

- Polyethylene (PE) with a prodegradant (e.g. TDPA\(^{\text{TM}}\))

- Polylactic Acid (PLA).

This streamlined LCA includes:

- An investigation of previous assumptions about degradation rates of different materials through a literature review and consultant with experts;

- Comparison of the various degradable resins most likely to be used for bag applications in Australia (subject to availability of data from the literature and manufacturers); and

- Comparison of degradable bags with other single use bags (LDPE, HDPE, paper, cotton and other natural fibre bags).

**Life cycle stages**

- **Goal and scope definition**

At the commencement of an LCA, the goal and scope of the study needs to be clearly defined. The goal should state unambiguously the intended application/purpose of the study, the audience for which the results are intended, the product or function that is to be studied, and the scope of the study. When defining the scope, consideration of the functional unit, system boundaries and data quality requirements are some of the issues to be covered.

- **Inventory analysis**

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\(^{29}\) Singlet HDPE, 50% recycled singlet HDPE, boutique LDPE (single use), reusable LDPE, calico, woven HDPE swag, PP fibre “Green Bag”, kraft paper – handled, solid PP “Smart Box” and biodegradable – starch based.
Inventory analysis is concerned with the collection, analysis and validation of data that quantifies the appropriate inputs and outputs of a product system. The results include a process flow chart (and a list of all environmental inventories (inventory table) that are associated with the product under study.

- **Impact assessment**

The primary aim of an impact assessment is to identify and establish a linkage between the product’s life cycle and the potential environmental impacts associated with it. The impact assessment stage consists of three phases that are intended to evaluate the significance of the potential environmental effects associated with the product system.

- **Interpretation**

Interpretation is a systematic evaluation of the needs and opportunities to reduce the environmental burden, such as changes in product, process and service design, and reductions in raw material and/or energy usage.

**Production processes for the degradable plastics**

**Starch polyester blends (Mater-Bi™)**

The starch polyester blend plastic identified as an appropriate material for shopping bags is the product with the trade name Mater-Bi™ produced by Novamont S.P.A in Italy. The raw material components of Mater-Bi™ are starch from maize, which is blended with a petroleum-based polyester (polycaprolactone - PCL), the latter provides water resistance and added strength (Stevens and Goldstein 2002) assumed to be a 50/50 mix between starch and PCL for the purposes of life cycle modeling. PCL is produced from cyclohexanone (95%) and acetic acid (5%) (Composto 1998) and is biodegradable through the action of nonspecific enzymes found in soil (Stevens 2003).

Table 18 presents the key data sources and assumptions that were used in constructing the inventory of the Mater-Bi™ polymer.

**Table 18 Data sources and key assumptions for life cycle inventory of the Mater-Bi™ polymer**

<table>
<thead>
<tr>
<th>Data</th>
<th>Source of data</th>
<th>Key assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>IVAM database</td>
<td>Based upon maize growing in the Netherlands.</td>
</tr>
<tr>
<td>Polycaprolacton</td>
<td>Description of process from (Composto 1998).</td>
<td>The production of polycaprolacton is produced from cyclohexanone (95%) and acetic acid (5%).</td>
</tr>
<tr>
<td>Cyclohexane</td>
<td>From IVAM database</td>
<td>The hydrogenation (H2 addition) of benzene (C6H6) results into the manufacture of cyclohexane (C6H10O). No specific water emissions and waste stream data available.</td>
</tr>
<tr>
<td>Acetic acid</td>
<td>Australian Data Inventories Report</td>
<td>Based upon data from the PEMS database. Is a base material input into terephthalate in PET.</td>
</tr>
</tbody>
</table>
Bionolle (polybutylene adipate terephthalate) (PBAT)

The first of the synthetic polyesters identified as being appropriate for shopping bag applications is made from polybutylene adipate terephthalate (PBAT) and has the trade name Bionolle, which is manufactured by Showa Highpolymer in Japan. Bionolle is based on the ester of succinic acid/adipic acid and 1,4-butanediol is used to make this biodegradable polymer. An example of a suitable commercially available diacid/diol aliphatic polyester is the polybutylene succinate/adipate copolymers sold as BIONOLLE 1000 series and BIONOLLE 3000 series. The ratio of components is:

- 12.5% - Succinic acid;
- 12.5% - Adipic acid;
- 25.0% - 1,4- butanediol; and
- 50.0% - High amylose starch

Bionolle is produced through polycondensation reactions of glycols (such as ethylene glycol and 1, 4-butanediol) with aliphatic dicarboxylic acids (such as succinic acid and adipic acid) (Mohanty et al. 2000).

The production processes for the raw material inputs into the Bionolle polymer are:

- 1,4-butanediol is derived either from natural gas or corn glucose (Pennington et al. 2001).
- Adipic acid is manufactured from cyclohexane in a continuous operation. Cyclohexane is air-oxidized, producing a cyclohexanol-cyclohexanone (ketone-alcohol, or KA) mixture. This mixture is then catalytically oxidized using 50 to 60 percent nitric acid, producing adipic acid. Phenol hydrogenation followed by nitric acid oxidation is the lesser-used method (US EPA 1991).
- Succinic acid is formed through the fermentation of corn-derived glucose (starch from maize is used as the default in the LCA modeling).

Due to data unavailabilities it was not possible to model the production of 1,4-butanediol and succinic acid, though terephthalate acid was used as a substitute. Table 19 presents the key data sources and assumptions that were used in constructing the inventory of the Bionolle polymer.

**Table 19 Data sources and key assumptions for life cycle inventory of Bionolle polymer**

<table>
<thead>
<tr>
<th>Data</th>
<th>Source of data</th>
<th>Key assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>See maize starch polyester blend polymer (see Table 18)</td>
<td>See maize starch polyester blend polymer (see Table 18) Assume PBAT polymer comprising 50% starch.</td>
</tr>
<tr>
<td>Adipic acid</td>
<td>Combination of data sources</td>
<td>Assume adipic acid is made of 60% nitric acid and 40% cyclohexane. Assume PBAT polymer comprising 25% adipic acid.</td>
</tr>
<tr>
<td>1,4-butanediol</td>
<td></td>
<td>60% formaldehyde and 40% ethene</td>
</tr>
<tr>
<td>Succinic acid</td>
<td></td>
<td>Starch from maize used as a default</td>
</tr>
</tbody>
</table>
EcoFlex™ (Polybutylene adipate terephthalate (PBAT))

The second synthetic polyester polymer is a polybutylene adipate terephthalate (PBAT), with a trade name of EcoFlex manufactured by BASF. Ecoflex is a statistical aliphatic-aromatic copolyester based on 1,4-butanediol and the dicarboxylic acids namely adipic acid and terephthalic acid. Its proper name is poly(tetramethylene adipate-co-terephthalate). The ratio of components is:

- 12.5% - Terephthalic acid;
- 12.5% - Adipic acid;
- 25% - 1,4- butanediol; and
- 50% - high amylose starch.

Table 20 presents the key data sources and assumptions that were used in constructing the inventory of the EcoFlex polymer.

Table 20 Data sources and key assumptions for life cycle inventory of EcoFlex polymer

<table>
<thead>
<tr>
<th>Data</th>
<th>Source of data</th>
<th>Key assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>See Table 18</td>
<td>See Table 18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Assume Ecoflex polymer comprising 50% starch.</td>
</tr>
<tr>
<td>Adipic acid</td>
<td>See Table 19</td>
<td>See Table 19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Assume Ecoflex polymer comprising 12.5% adipic acid.</td>
</tr>
<tr>
<td>Terephthalic acid</td>
<td>Australian Data Inventories project.</td>
<td>Base material in production of PET. Data based upon IVAM and PEMS data. Assume Ecoflex polymer comprising 12.5% terephthalic acid.</td>
</tr>
<tr>
<td>1,4-butandiol</td>
<td>See Table 19</td>
<td>See Table 19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Assume Ecoflex polymer comprising 12.5% 1,4-butandiol which is modelled as terephthalic acid.</td>
</tr>
</tbody>
</table>

Earthstrength tapioca starch polymer

A starch-polyethylene blend polymer suitable for film blowing into shopping bags is the product commercially known as Earthstrength. The starch is sourced from tapioca (cassava) and current technology enables of 30% starch/70% high-density polyethylene blend. Table 21 presents the key data sources and assumptions that were used in constructing the inventory of the Earthstrength polymer.
Table 21 Data sources and key assumptions for life cycle inventory of the Earthstrength polymer

<table>
<thead>
<tr>
<th>Data</th>
<th>Source of data</th>
<th>Key assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDPE</td>
<td>Australian Data Inventories project</td>
<td>Adapted from Chalmers University Polymerisation data 1991. For high-density polyethylene two-ethylene feedstock are used at the Kemcor site in Altona Victoria. Data has been corrected for Australian energy and feedstock types, however no validation of energy involved in polymerisation has been undertaken.</td>
</tr>
<tr>
<td>Cassova</td>
<td>IVAM 4 database</td>
<td>Mixed data</td>
</tr>
</tbody>
</table>

**Oxo-biodegradable polymers (Prodegradant in standard polyethylene)**

Activated polyolefins are polyolefins such as polyethylene (PE) or polypropylene (PP) can have an additive that enhances environmental degradation. Additives are incorporated (approximately 3% by weight) into the polymer during processing to induce accelerated oxidative degradation initiated by natural daylight, heat and/or mechanical stress (Stevens and Goldstein 2002). Table 22 presents the key data sources and assumptions that were used in constructing the inventory of the oxo-biodegradable polymer.

Table 22 Data sources and key assumptions for life cycle inventory of oxo-biodegradable polymer

<table>
<thead>
<tr>
<th>Data</th>
<th>Source of data</th>
<th>Key assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDPE</td>
<td>Australian Data Inventories project</td>
<td>Adapted from Chalmers University Polymerisation data 1991. For high-density polyethylene two-ethylene feedstock are used at the Kemcor site in Altona Victoria. Data has been corrected for Australian energy and feedstock types, however no validation of energy involved in polymerisation has been undertaken.</td>
</tr>
<tr>
<td>Stearic acid</td>
<td>IVAM 4 database</td>
<td></td>
</tr>
<tr>
<td>Cobalt</td>
<td>IDEMAT 2001 database</td>
<td>Average data.</td>
</tr>
</tbody>
</table>

**Polylactic acid**

Polylactic acid is a linear aliphatic thermoplastic polyester polymer. It is chemically synthesised by one of two processes: poly-condensation of the free acid or by catalytic ring-opening polymerisation of the lactide (dilactone of lactic acid) (Bastioli 1997).

Table 23 presents the key data sources and assumptions that were used in constructing the inventory of the PLA polymer.
Table 23 Data sources and key assumptions for life cycle inventory of PLA polymer

<table>
<thead>
<tr>
<th>Data</th>
<th>Key assumptions and data sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn growing and harvesting, production of dextrose, lactic acid and polymerisation of polylactic acid</td>
<td>Based upon maize growing in the United States of America. Energy values were given in (Vink et al. 2003) and these have been modelled. Linked to US data sources.</td>
</tr>
</tbody>
</table>

End-of-life waste treatment technology descriptions

Descriptions of the technologies investigated are presented in two sections below – source separated organics and residual treatment (Grant et al. 2003b).

- **Landfill**

  Involves direct dumping of material into clay lined (or synthetically lined) cells where waste is compacted and covered on a daily basis with dirt. Pipes for collecting gas and leachate from the landfill are built into the waste piles as they are constructed. Collected gas may be flared or used for energy production.

- **Source Separated Organics**

  - **Aerobic Composting**: Composting of organic material. This usually involves shredding, placing in piles or windrows (with partial forced aeration when food waste is present), turning and refining. Benefits are achieved with application of the compost product (from the process) to land.

  - **Anaerobic Digestion**: Processing of organic material in a digester (i.e., in the absence of air), generation of biogas that is converted to electricity, composting of digester output. Benefits are achieved with application of the compost product (from the process) to land.

- **Residual Waste Treatment**

  Processing of residual waste (a.k.a. mixed waste or garbage) prior to landfilling in order to reduce volume of waste landfilled; reduce landfill gas and leachate emissions; and recover energy and additional recyclables.

  - **Aerobic Stabilisation**: Particle size reduction, homogenisation, composting to reduce putrescible substances, landfiling of ‘stabilised’ material (which has reduced volume and emission potential), and recovery of metals and organic material as compost.

  - **Anaerobic Digestion**: Particle size reduction, homogenisation, processing of organic material in a digester (i.e., in the absence of air), generation of biogas which is converted

---

30 It should be noted that the digester feedstock would be predominantly food waste, with the bulkier garden waste being added at the end of the process (i.e., composting).
to electricity, composting of digester output, landfilled of ‘stabilised’ material, and recovery of metals and some organic material as compost.

A range of assumptions had to be made for modelling the scenarios. These are described in detail in the main report. Table 24 lists some of the key assumptions for the technologies and scenarios.

**Table 24 Key assumptions for the study**

<table>
<thead>
<tr>
<th>Process</th>
<th>Key assumptions</th>
</tr>
</thead>
</table>
| Dynamics at landfill (MSW)            | • Values for methane generation from organic fractions taken from (Smith 2001).  
• Assume landfill gas capture is in place in landfills accounting for 80% of overall methane generated/emitted from landfills. Of the 80%, assume 55% of methane is captured, and of this 55%, 75% results in electricity production the remaining 25% is flared. Of the remaining 45% not captured, assume 10% degrades through the landfill cap.  
• CO₂ is also sequestered in the landfill.  
| Composting green and food waste       | • 45-55% of input to process is output compost  
| Anaerobic digestion (green and food waste) | • Digestion is followed by aerobic compost production  
• 30-50% of input to process is output compost.  
• 80 – 100 kWh/t net electricity output.  
| Aerobic stabilisation (MSW)           | • 60-70% of input to process is output. Of this 34% is compost and 66% is stabilised residue sent to landfill. Automated ferrous metal recovery.  
| Anaerobic digestion (MSW)             | • Digestion is followed by aerobic curing  
• 55-65% of input to process is output. Of this 28% is low-grade compost and 72% is stabilised residue sent to landfill. Automated ferrous metal recovery.  
• 0-20 kWh/t input net electricity output  
| Benefits of using compost (from green and food waste) | • 3% increase in crop yield through increase in water holding capacity (estimated on wheat crop)  
• Fertiliser replacement of 1.5% N and 0.25% for K and P.  
• Nitrous oxide emissions.  
• 20% reduction in pesticide use.  
• 10% of carbon is sequestrated in the land.  
| Benefits of using compost (from MSW)  | • 10% of carbon is sequestrated in the land.  

**Source:** (Grant et al. 2003b).

**Life cycle impact assessment**

The environmental indicators included in the study are:

- **Global warming** – Climate change effects resulting from the emission of CO₂, methane or other greenhouse gases into the atmosphere – this indicator is represented in CO₂ equivalents.
• **Resource Depletion** - The depletion of non-living (abiotic) resources from the environment taking account of the abundance of these resources and current usage patterns. This indicator is represented in Antimony (Sb) equivalents (Antimony is a relatively rare metal used in metal alloys, semiconductors, and many other uses).

• **Eutrophication** – This is the release of nutrients (mainly phosphorous and nitrogen) into land and water systems, altering biota, and potentially increasing algal growth and related toxic effects.

• **Litter Marine Biodiversity Indicator** – Based on the time and mass on material available for ingestion or entanglement by marine fauna. Literature values suggest plastic films at sea which float may last up to 6 months before they are weighted down by algal growth, or washed ashore. This time was taken as the basis for assessing non-degrading films that had potential to float. For the oxo-biodegradable technology, while the material will float, it was thought that, through partial degradation the material would sink faster than conventional plastic so it was allow three months to sink.

• **Litter Aesthetic Indicator** – This indicator attempts to represent the visual impact of litter, which was taken to be related to the areas of the material and the time before it would degrade.
### Impact assessment values

#### Table 25 Greenhouse values for the degradable polymers and alternative bags

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Unit</th>
<th>Bionelle Bag-1 year baseline disposal</th>
<th>Eco-Flex Bag-1yr baseline disposal</th>
<th>Mater-Bi Bag-1 year baseline disposal</th>
<th>Earth-strength Bag-1 year baseline disposal</th>
<th>Oxo-biodegradable Bag-1 year baseline disposal</th>
<th>PLA Bag-1 year baseline disposal</th>
<th>HDPE Singlet-1 year</th>
<th>Kraft Paper Coles Handled-1 year</th>
<th>PP Fibre Green Bag-1 year</th>
<th>Woven HDPE Swag Bag-1 year</th>
<th>Calico Bag-1 year</th>
<th>LDPE bag for life Bag-1 year</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>g CO₂</td>
<td>3090</td>
<td>3670</td>
<td>5460</td>
<td>4950</td>
<td>5600</td>
<td>14200</td>
<td>5680</td>
<td>18800</td>
<td>1870</td>
<td>590</td>
<td>2020</td>
<td>2550</td>
</tr>
<tr>
<td>Methane</td>
<td>g CH₄</td>
<td>84.60</td>
<td>78.30</td>
<td>119</td>
<td>37.80</td>
<td>21.10</td>
<td>144</td>
<td>18.20</td>
<td>755</td>
<td>3.78</td>
<td>1.70</td>
<td>34.00</td>
<td>8.04</td>
</tr>
<tr>
<td>N₂O</td>
<td>g N₂O</td>
<td>5.54</td>
<td>4.45</td>
<td>5.99</td>
<td>2.70</td>
<td>0.06</td>
<td>10.70</td>
<td>0.05</td>
<td>1.95</td>
<td>0.01</td>
<td>0.01</td>
<td>0.90</td>
<td>0.02</td>
</tr>
<tr>
<td>Sequestration</td>
<td>g CO₂</td>
<td>-305</td>
<td>-521</td>
<td>-412</td>
<td>-91.60</td>
<td>x</td>
<td>-412</td>
<td>x</td>
<td>-4770</td>
<td>x</td>
<td>x</td>
<td>-456</td>
<td>x</td>
</tr>
<tr>
<td>Other</td>
<td>g CO₂ eq</td>
<td>1.29</td>
<td>1.04</td>
<td>1.37</td>
<td>0.61</td>
<td>0.00</td>
<td>0.93</td>
<td>x</td>
<td>0.26</td>
<td>x</td>
<td>x</td>
<td>0.31</td>
<td>x</td>
</tr>
</tbody>
</table>

#### Table 26 Resource (abiotic) depletion values for the degradable polymers and alternative bags

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Unit</th>
<th>Bionelle Bag-1 year baseline disposal</th>
<th>Eco-Flex Bag-1yr baseline disposal</th>
<th>Mater-Bi Bag-1 year baseline disposal</th>
<th>Earth-strength Bag-1 year baseline disposal</th>
<th>Oxo-biodegradable Bag-1 year baseline disposal</th>
<th>PLA Bag-1 year baseline disposal</th>
<th>HDPE Singlet-1 year</th>
<th>Kraft Paper Coles Handled-1 year</th>
<th>PP Fibre Green Bag-1 year</th>
<th>Woven HDPE Swag Bag-1 year</th>
<th>Calico Bag-1 year</th>
<th>LDPE bag for life Bag-1 year</th>
</tr>
</thead>
<tbody>
<tr>
<td>abiotic depletion</td>
<td>kg Sb eq</td>
<td>0.0191</td>
<td>0.034</td>
<td>0.055</td>
<td>0.0722</td>
<td>0.0951</td>
<td>0.107</td>
<td>0.0998</td>
<td>0.273</td>
<td>0.0219</td>
<td>0.00921</td>
<td>0.0587</td>
<td>0.0411</td>
</tr>
</tbody>
</table>
### Table 27 Eutrophication values for the degradable polymers and alternative bags

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Unit</th>
<th>Bionelle Bag-1 year baseline disposal</th>
<th>Eco-Flex Bag-1 yr baseline</th>
<th>Mater-Bi Bag-1 year baseline disposal</th>
<th>Earth-strength Bag-1 year baseline disposal</th>
<th>Oxo-biodegradable Bag-1 year baseline</th>
<th>PLA Bag-1 year baseline disposal</th>
<th>HDPE Singlet-1 year</th>
<th>Kraft Paper Coles Handled-1 year</th>
<th>PP Fibre 'Green Bag'-1 year</th>
<th>Woven HDPE Swag Bag-1 year</th>
<th>Calico Bag-1 year</th>
<th>LDPE bag for life Bag-1 year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eutrophication</td>
<td>kg PO4 eq</td>
<td>0.256</td>
<td>0.207</td>
<td>0.278</td>
<td>0.124</td>
<td>0.00253</td>
<td>0.83</td>
<td>0.00246</td>
<td>0.0266</td>
<td>0.00127</td>
<td>0.000231</td>
<td>0.00979</td>
<td>0.00114</td>
</tr>
</tbody>
</table>

### Table 28 Litter values for the degradable polymers and alternative bags

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Unit</th>
<th>Bionelle Bag-1 year baseline disposal</th>
<th>Eco-Flex Bag-1 yr baseline</th>
<th>Mater-Bi Bag-1 year baseline disposal</th>
<th>Earth-strength Bag-1 year baseline disposal</th>
<th>Oxo-biodegradable Bag-1 year baseline</th>
<th>PLA Bag-1 year baseline disposal</th>
<th>HDPE Singlet-1 year</th>
<th>Kraft Paper Coles Handled-1 year</th>
<th>PP Fibre 'Green Bag'-1 year</th>
<th>Woven HDPE Swag Bag-1 year</th>
<th>Calico Bag-1 year</th>
<th>LDPE bag for life Bag-1 year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Litter Marine Biodiversity</td>
<td>kg.y</td>
<td>4.26E-05</td>
<td>4.26E-05</td>
<td>5.75E-05</td>
<td>7.80E-03</td>
<td>3.90E-03</td>
<td>5.75E-05</td>
<td>7.80E-03</td>
<td>3.02E-04</td>
<td>2.41E-04</td>
<td>1.07E-04</td>
<td>3.09E-06</td>
<td>2.57E-03</td>
</tr>
<tr>
<td>Litter Aesthetics</td>
<td>m².y</td>
<td>0.078</td>
<td>0.078</td>
<td>0.078</td>
<td>0.078</td>
<td>0.078</td>
<td>0.078</td>
<td>0.312</td>
<td>0.078</td>
<td>1.87E-03</td>
<td>1.49E-03</td>
<td>1.64E-03</td>
<td>7.46E-03</td>
</tr>
</tbody>
</table>