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Assessing the Environmental Impacts of Oxo-degradable Plastics Across Their Life Cycle

Loughborough University

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Report to the Department for Environment, Food and Rural Affairs

Date (January/2010)

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Glossary

Aerobic	(of a process) carried out in the presence of oxygen.
Anaerobic	(of a process) carried out in the absence of oxygen.
Antioxidant	A substance that inhibits the oxidative degradation of a polymer.
ASTM D6400	American standard specification for compostable plastics.
Bio-accumulation	The build-up of a chemical or substance in a plant or animal, either individual or population, over a period of time.
Biodegradability	The breakdown of an organic chemical compound by micro-organisms in the presence of oxygen to carbon dioxide, water and mineral salts of any other elements present (mineralization) and new biomass or in the absence of oxygen to carbon dioxide, methane, mineral salts and new biomass (from EN13432)
Biodegradable plastic	a degradable plastic in which the degradation results from the action of naturally occurring microorganisms such as bacteria, fungi and algae (ASTM D 6400-99)
Bio-degradation	Degradation brought about by the action of naturally occurring micro-organisms such as bacteria, fungi and algae
Composting	A managed process that involves the biological decomposition and transformation of biodegradable material to produce carbon dioxide, water, minerals and organic matter (compost or humus)
Cross-linking	Cross-linking is a chemical process in which polymer molecules join together to form a network structure.
DDE	A chlorinated pesticide associated with a number of toxic effects on humans and animals. It has many chemical pseudonyms including <i>1,1-dichloro-2,2-bis(p-chlorophenyl)ethylene</i> .
DDT	(dichlorodiphenyltrichloroethane) A chlorinated pesticide, banned under the Stockholm Convention, although still in use as an agricultural insecticide. It is strongly adsorbed by soils.
Defra	Department for Environment, Food and Rural Affairs
Degradation	A change in the chemical structure of a plastic involving a deleterious change in properties
Disintegration (syn. fragmentation)	The physical breakdown of a material into very small fragments. (After ISO/DIS 17088)
EA	Environment Agency
Electron spin resonance spectroscopy	An analytical technique which detects free radicals in a material.
EN 13432	European standard for packaging recoverable through composting and biodegradation.

Fossil Carbon	Carbon derived from fossil fuels (oil, coal, gas)
Fourier Transform Infrared Spectroscopy	An analytical technique capable of detecting chemical bonds in a compound. It is a useful tool for detecting the presence of oxidised polymers.
Fragmentation	See Disintegration.
ISO/DIS 17088	Life Cycle Assessment. A process for assessing various impacts of a process or material or technology by considering all inputs and outputs throughout its lifetime. <i>(previously known as Life Cycle Analysis)</i>
LCA	
Masterbatch	A formulation containing a high concentration of additive intended for dilution into a pure resin (plastic) during processing to produce the end product.
Nonylphenols	A class of industrial surfactant or detergent. Although used widely outside the EU, within the EU they are replaced by less harmful alternatives such as alcohol ethoxylates.
Oxidative Degradation	A complex series of chemical reactions in which the long chains of polyethylene molecules are broken down into shorter lengths by the action of oxygen, ultra-violet light and/or heat.
PAH	Polycyclic aromatic hydrocarbon. Organic compounds found in coal, oil and tar. Also produced by incomplete combustion of many materials. Some PAHs are known to be highly carcinogenic. They are much more soluble in oil than water and are strongly adsorbed by materials such as polyolefins.
PCB	Polychlorinated biphenyl: A class of compounds implicated in a number of human toxicity and environmental pollution incidents. Production was banned in 2001 by the Stockholm Convention on Persistent Organic Pollutants.
PE	Polyethylene
PET	Polyethylene Terephthalate
Phytotoxicity	Toxicity to plants
PP	Polypropylene
Prooxidant	A substance that promotes the oxidative degradation of a polymer.
PVC	Polyvinylchloride
Robustness	An overall measure of the quality of evidence, including criteria such as reliability of source and objectivity. Robustness in this report is assessed according to the Defra guidelines "Five Components of Robust Evidence".
Windrow composting	A composting process in which the material to be composted is formed into long piles which are turned at intervals so as to ensure all the medium experiences the composting conditions in the centre of the pile. The process may be done outdoors or under cover.

Executive Summary

This report addresses the environmental impact of oxo-degradable plastics. These plastics are mainly based on polyethylene (polythene) and contain additives that cause the plastic to degrade by a process initiated by light and/or heat. The additives are typically organic compounds of transition metals (such as iron, nickel, cobalt and manganese). Applications using oxo-degradable plastics include degradable plastic bags, refuse sacks, flexible packaging and agricultural mulch films.

The reason for using these additives in plastic packaging or film is to cause premature degradation of the product. For example, it is claimed by the producers that agricultural mulch film containing these additives will break down and effectively disappear at the end of the growing season, thus saving farmers the time and cost in collecting it. Similarly, the producers claim that oxo-degradable plastic bags that are released into the environment as litter will degrade and disintegrate in a much-reduced time.

Aims and Methodology

The aim of this study is to assess the evidence for the effects (both positive and negative) of oxo-degradable plastics on the environment, across their life-cycle. The difference between oxo-degradable plastics and other petroleum based plastics is the use of additives to give them the accelerated property of degradation, hence the focus of the study was on the environmental effects at disposal or end of life. In particular the study has assessed:

- The extent and timeframe of degradation or biodegradation of oxo-degradable plastics.
- The effects of degradation or biodegradation of oxo-degradable plastics on the natural environment (e.g. soil, water) and different disposal facilities (e.g. recycling, landfill, compost)

The methodology employed in the study has been to review the published research on oxo-degradable plastics, assess other literature available in the public domain, and also to engage with stakeholders throughout the life-cycle of the product, including the additive manufacturers, producers, retailers, end-users and those involved in recycling and composting.

Issues for Examination

The most important issue regarding oxo-degradable plastics is the extent to which they degrade or biodegrade and the impact of this on the environment. There are various claims made on degradable packaging, such as: 'photodegradable polythene', '100% degradable plastic', '100% biodegradable', 'the plastic will start to degrade in 18 months from the date of manufacture and the whole process will take 3 years'. The extent to which such claims can be substantiated has formed an important element of the investigation reported here.

A key question is whether oxo-degradable plastics **biodegrade** (i.e. whether the plastic can be colonised and metabolised by microbes) and if so, what is the extent and time frame of this process.

That oxo-degradables do **degrade** when exposed to either sunlight or heat (~60°C) is

not in any doubt. The additives serve to catalyse and accelerate break-down of the polyethylene by a process known as oxidative degradation.¹The mechanisms of these reactions have been studied over a period of several decades and are widely reported and well established in the scientific literature. This degradation process causes deterioration in the strength of the plastic, which becomes brittle and easily fragments into small pieces. The time taken for fragmentation to occur will depend on the amount of additive in the plastic film and the environment to which it is exposed. For example, degradation reactions leading to fragmentation of polythene films will occur much more quickly in Florida compared with the UK because of the differences in the intensity of the sunlight.

Biodegradation, however, is caused by the action of living organisms rather than physical or chemical processes. However, the term **biodegradable** does not specify the extent, time-scale or conditions under which biodegradation has taken place. The term **compostable** is more precisely defined. According to the European standard on compostable packaging materials, EN13432, a biodegradation level of at least 90% must be achieved in less than six months for a plastic to be described as compostable. This study examined (so far as was possible) the length of time it would take for oxo-degradable plastics to degrade and bio-degrade, although there were limitations in the evidence beyond 6 months to 1 year.

Furthermore, after the oxo-degradable plastics start to degrade it is unclear what happens to the small fragments of plastic in the environment. Are they able to be completely assimilated by micro-organisms (bacteria, fungi and/or algae) and ultimately converted to carbon dioxide and water vapour, so that they disappear? Does it matter if they remain as fragments in the soil? Does it matter if they become air-borne or enter water courses?

Consequently this study has reviewed the timeframe within which oxo-degradable plastics biodegrade and the effects of the degraded plastics and additives on the environment. Evidence of **biodegradation** of oxo-degradable plastics has formed a major element of this review. Also examined is the potential for **bio-accumulation** of plastic fragments that remain in the soil. Another issue examined is the potential for transition metal additives to accumulate in the soil and hence to have a toxic effect on plants and potentially enter the human food chain. Hence **toxicological** studies on oxo-degradable plastics have also been reviewed.

Other issues examined are **re-use** of oxo-degradable bags and end-of-life scenarios including **recycling** (i.e. the impact of oxo-degradables on mechanical recycling), **incineration** and also **landfill**.

The key findings and recommendations of the report are summarised below.

1. Key findings

The overall conclusion of this review is that incorporation of additives into petroleum-based plastics that cause those plastics to undergo accelerated degradation does not improve their environmental impact and potentially gives rise to certain negative effects.

(a) Degradation and biodegradation

¹ **Oxidative degradation** is a complex series of chemical reactions in which the long chains of polyethylene molecules are broken down into shorter lengths by the action of oxygen, ultra-violet light and/or heat).

- The length of time to degradation of oxo-degradable plastic cannot be predicted accurately because it depends so much on the environmental conditions. It is suggested that oxo-degradable plastics left in the open environment in the UK degrade to small fragments within 2 to 5 years.
- Oxo-degradable plastics are not compostable, according to established international standards EN13432 and ASTM 6400. Oxo-degradable plastics should not be included in waste going for composting, because the plastic fragments remaining after the composting process might adversely affect the quality and saleability of the compost.
- It is thought that labelling the oxo-degradable plastics as biodegradable can lead to confusion on the part of consumers, who may assume that 'biodegradable plastics' are compostable. This may lead to contamination of the composting waste-stream with oxo-degradable plastics.
- Biodegradation of oxo-degradable plastics can only occur after they have fragmented and then proceeds very slowly, for example, at a rate many times slower than that of a compostable plastic.
- The fact that the term "biodegradable" can be applied to materials with extremely widely differing rates of biodegradation demonstrates that the term is virtually meaningless unless the rates of biodegradation and conditions under which it is measured are specified, preferably with reference to a widely recognised standard.

(b) Bio-accumulation of plastic fragments in the environment

The fate of plastic fragments that remain in the soil is an area of uncertainty. Although these are regarded as beneficial by the producers, concerns have been raised that these particles of plastic may be ingested by invertebrates, birds, animals or fish. No evidence was found in this study that oxo-degradable fragments have a harmful bio-accumulative effect but neither was there evidence that they do not.

(c) Toxicological Impact

No evidence of a toxicological impact of oxo-degradable additives was found in this review. It is concluded that the transition metals used are present in such small amounts that they will not significantly increase the concentrations naturally present in the soil at expected levels of usage.

(d) Re-use

The fact that they are degradable limits the re-use of oxo-degradable bags: they are unsuitable for storing items for an extended length of time.

(e) Recycling

Oxo-degradable plastics are not suitable for recycling with main-stream plastics. The recycle will contain oxo-degradable additives that will render the product more susceptible to degradation. Although the additive producers suggest that stabilisers can be added to protect against the oxo-degradable additives, it would be problematic for recyclers to determine how much stabiliser needs to be added and to

what extent the oxo-degradable plastic has already degraded. On this basis it seems unreasonable to claim recyclability of oxo-degradable plastics in existing recycling streams.

(f) Disposal – Incineration and Landfill

The potential for problems to be caused by incorrect disposal of oxo-degradable plastics means that any packaging should be clearly labelled with the appropriate means of disposal. Life cycle analysis suggests that the best means of disposal for oxo-degradable plastics is incineration. If incineration is not available then landfill is the next best option.

There is a lack of evidence about what actually happens to oxo-degradable plastics in landfill. It is possible that they will degrade in landfill sites if sufficient oxygen is present but the most likely scenario is that they remain un-degraded.

(h) Litter

Some oxo-degradable producers maintain that their products are a solution to the littering problem because oxo-degradable packaging will eventually degrade and then biodegrade. However, as the plastics will not degrade for approximately 2-5 years, they will still remain visible as litter before they start to degrade.

2. Recommendations

The recommendations regarding oxo-degradable plastics made on the basis of all the evidence reviewed in this study from the peer-reviewed literature, non-peer-reviewed literature (reports and websites) and also from stakeholder interviews are given below.

- The term 'biodegradable' does not indicate the environment or timescale required for biodegradation to occur and is therefore problematic for labelling packaging. There are two possible solutions to this:-
 - (i) One solution is that if the term 'biodegradable' is used then it is necessary to define the disposal environment, extent of biodegradation in a short given time period or the time taken to complete biodegradation.
 - (ii) The other solution is not to use the term 'biodegradable' for labelling packaging at all, but to only label with instructions on the means of disposal.
- The fate of oxo-degradable plastic after it has fragmented to a fine powder is not clear. Therefore it is recommended that further research is carried out to determine whether complete degradation to carbon dioxide and water is achieved, and if so, over what time scale. If the fine particles are found to persist in the environment for a long period of time, research should be carried out to determine the effect of the particles on the wider environment.
- The uncertainties surrounding the effect of oxo-degradable plastics on the conventional plastics recycling process means that the safest solution is to keep oxo-degradable plastics out of mainstream plastics recycling processes.

1 Introduction and objectives

1.1 Introduction

The subject of this study is oxo-degradable plastics and their impact (positive or negative) on the environment. Oxo-degradable plastics are mostly made of polyethylene (PE) but may be made of polypropylene (PP). They are plastics that contain special additives that cause them to degrade after a certain amount of exposure to either sunlight or heat. The time over which the degradation process takes place depends on the concentration of additive in the plastic and the amount of sunlight and/or heat to which it is exposed.

The aim of this research project is to review existing data and published research on the environmental impact of oxo-degradable plastics during their whole life cycle. In addition to the hard data and evidence collected in reviewing the published literature, the project has also involved interviewing stakeholders. The reason for engaging with stakeholders has been to gauge perceptions of the environmental impact of these materials. The stakeholders have included additive manufacturers and masterbatch producers, retailers, end-users and those involved in end-of-life issues such as recycling and composting.

A key driver for this project was to assess the evidence behind the claims being made about oxo-degradable plastics. They are variously described as '100 % degradable' or '100% biodegradable' but it is not clear what is meant by this. What is the evidence that these materials actually degrade or biodegrade and under what conditions and over what timescale?

1.2 Objectives

The purpose of the research is to assess the environmental impact (both positive and negative) of oxo-degradable plastics. The specific objectives of the project are enumerated below:-

1. To gather and review existing data, research and stakeholder views on the environmental impact of oxo-degradable plastics across their life-cycle.
2. To assess the evidence of the impact of oxo-degradables on the environment considering the following :-
 - What happens to the polymers and metal salts after the oxo-degradable plastics disintegrate?
 - Are the claims that oxo-degradable plastics degrade or biodegrade completely, often within a certain timeframe, accurate? What is the evidence to support this?
 - How do oxo-degradable plastics affect the recycling stream? Do they contaminate recycling and affect the value or application of the recycled product?
 - How do oxo-degradable plastics behave in, and affect, other disposal environments such as composting and landfill?
 - What is the wider effect of oxo-degradable plastics if they are left to degrade the natural environment? This addresses issues such as toxicity and bioaccumulation.

- How would the environmental impacts of an oxo-degradable product compare with the environmental impacts of the same product without the additive?
3. To identify any deficits of information that prevent a completely confident assessment being made

The main focus of the study has been evidence for degradability, biodegradability, bio-accumulation, toxicity and the impact on recycling. Hence, in the conclusion and results sections (sections 2 and 4), the work is considered under these headings.

1.3 Context

To set oxo-degradable plastics in context, some information is given here about the types of additives used and the applications that have been developed so far.

The additives used in oxo-degradable plastics are usually metal salts of carboxylic acids or dithiocarbamates. The additive producers do not precisely disclose the concentration or types of metals used (Annex C) but it seems from the literature that the metals are typically transition metals, such as iron, nickel, cobalt and manganese. The additives catalyse the break-down of the long molecular chains in the plastic material (whether polyethylene or polypropylene or polystyrene). This degradation process is caused by the action of oxygen and ultra-violet light and/or heat. The reaction is accelerated by the metal ions present. This causes the plastic to become brittle and fragment into small pieces, which then become distributed in the environment.

The sorts of applications in which oxo-degradable additives are utilized are plastic films in a range of products for agricultural, packaging and waste disposal applications. The reason for using them is that they cause premature degradation of the product.

One application is agricultural mulching films for growing a whole range of fruits and vegetables. These are used in various parts of the world to provide a controlled environment for crop growth e.g. conserving water or protecting against frost. The use of oxo-degradable additives is purported to cause disintegration of the film at the end of the growing cycle and hence it does not need to be collected, thus saving time and money for farmers. Note that the Environment Agency (EA) has banned the ploughing in of these materials in the UK.

Other potential agricultural uses are silage wrap, grow bags and plant pots – the latter being made of polystyrene¹

. Another major use of oxo-degradables is in plastic carrier bags and some other forms of plastic bags used for packaging either food or clothes.

Some very specific claims are made on these products, indicating that there is an environmental benefit in their use. For example: *this bag is made from 100% biodegradable plastic; this bag is 100% degradable and recyclable; this bag is made from 100% degradable polythene – it will totally degrade after 12 to 18 months of being buried in the ground.* See Figure 1.1 below. Such claims may give rather confusing messages to the public in terms of the use, re-use and disposal of this type of packaging.

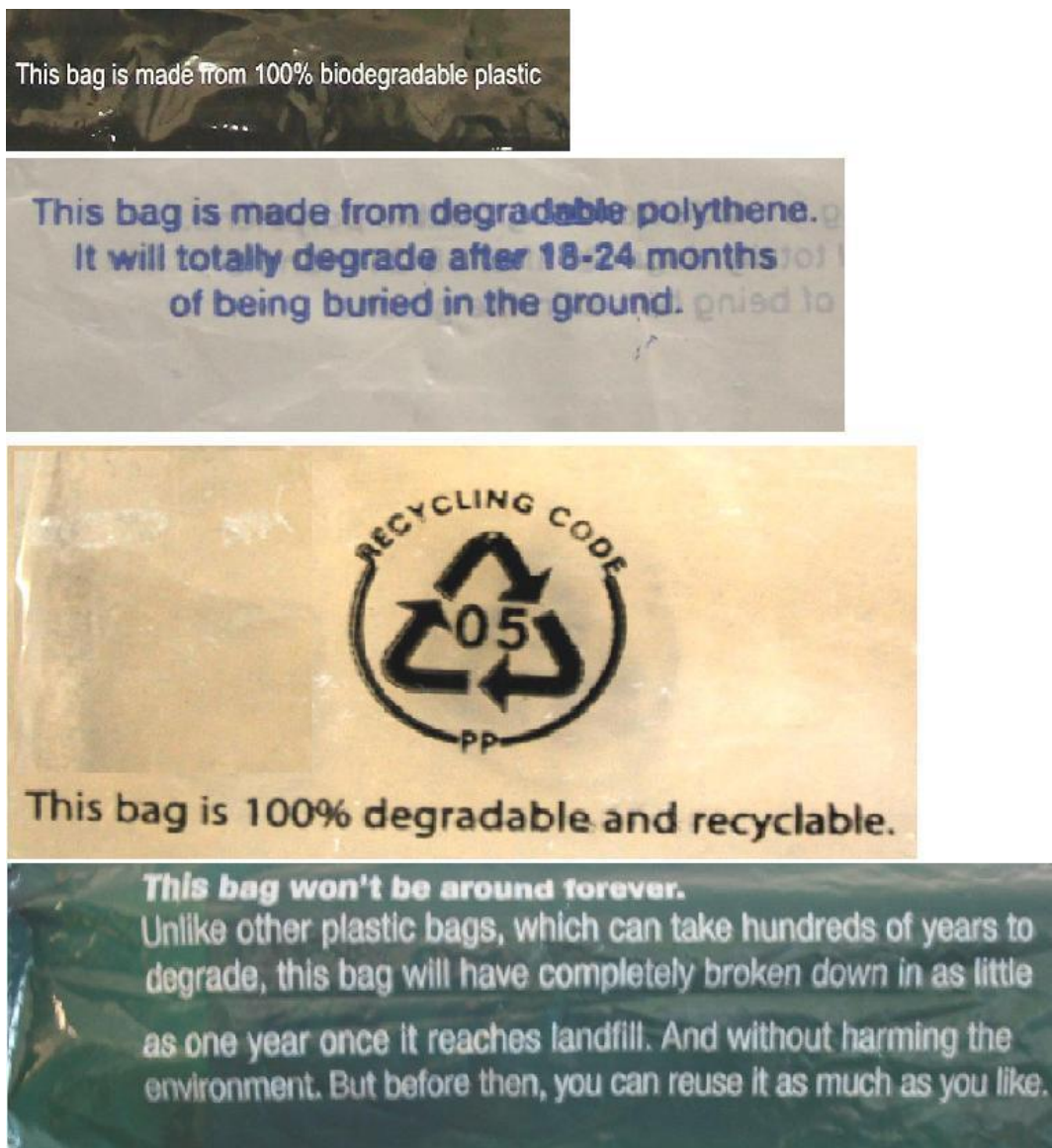


Figure 1.1. Examples of Claims made on Oxo-degradable Plastic Packaging

Another major application is in packaging used for waste disposal, such as refuse sacks and composting sacks²

. The functionality of these products relies on their degradability and biodegradability, which is discussed in detail in the other parts of this report. See section 4 and Annex C.

Evidence for degradation of oxo-degradable packaging is not difficult to come by and there is no doubt that when exposed to sunlight for an extended period of time, the plastic will become embrittled and fragment, as illustrated in Figure 1.2 below. Obviously, the time required depends on the strength of the sunlight and will clearly be much quicker in the Middle East, for example, than in the temperate climate of northern Europe.



Fig 1.2. Illustrating Degradation of an Oxo-degradable Carrier Bag

The chemical mechanism by which this fragmentation process takes place is known as oxidative degradation and it has been studied for many years. It is widely reported and accepted in the scientific literature³.

Less clear is the extent to which these fragments of plastic are biodegradable i.e. capable of being metabolised by microbes and converted into carbon dioxide and water. Investigation of this evidence has formed a major part of the current report.

Detailed information about the size of the market for these materials is outside the scope of this report. Although information from two of the major producers suggests that the market is increasing in volume and in geographical spread. One company has seen a spread of interest in North and South America, the Middle East, India and Eastern European countries. According to their website, another company sells their additive in 60 countries with thousands of tonnes of oxo-degradable product made per annum.

1.4 Degradability, Biodegradability and Compostability

The **degradation** of oxo-degradable plastics is due to a chemical process known as oxidative degradation, when the plastic is exposed to heat or light. **Oxidative degradation** is a complex series of chemical reactions in which the long chains of polyethylene molecules are broken down into shorter lengths by the action of oxygen, ultra-violet light and/or heat.

Biodegradation is a biological process that occurs only after the plastics have started to degrade. A biodegradable plastic is defined in EN ISO 472:2001 as: “degradable plastic in which degradation results in lower molecular weight fragments produced by the action of naturally occurring microorganisms such as bacteria, fungi and algae”. In the American standard ASTM D 6400-04 it is defined as: “a degradable plastic in which the degradation results from the action of naturally occurring microorganisms such as bacteria, fungi and algae”. In both of these definitions, it is stated explicitly that the degradation is brought about by the action of living organisms rather than physical or chemical processes.

A **compostable** plastic is defined by the ASTM D 6400 standard as: “A plastic that undergoes degradation by biological processes during composting to yield CO₂, water, inorganic compounds and biomass at a rate consistent with other known compostable materials and leaves no visible, distinguishable or toxic waste”. The process of composting is defined in the British standard PAS 100:2005 “Specification for Composted Materials” as a “process of controlled biological decomposition of biodegradable materials under managed conditions that are predominantly aerobic and that allow the development of thermophilic temperatures as a result of biologically produced heat”. To be compostable, a plastic must biodegrade within 180 days.

1.5 Disposal Routes

The main disposal routes for plastics waste are: mechanical recycling; incineration (with or without energy recovery) and landfill.

Recycling is the reprocessing of waste material, usually by combining it with fresh or ‘virgin’ material in such proportions that the properties of the latter are not compromised. There are currently limited facilities for recycling, although these are expected to increase as legislation on recycling becomes tighter. Barriers to recycling include: the high volume to weight ratio of waste plastic, which makes it expensive to collect, store and transport; high levels of contamination, which compromise the quality of the recyclate; the wide range of plastics, which requires sorting and the low market price for recyclate.

Incineration is a controlled burning process which destroys waste or transforms it into less hazardous or bulky constituents. Energy from Waste (EfW) plants harness the heat from combustion to produce energy, thus the calorific value of the waste is of prime importance. At present, there are fifteen EfW plants operating in the UK. However EfW plants are generally not received well by the public and are often associated with harmful emissions and greenhouse gases although these plants are tightly controlled by the Environmental Protection Act (1990) and EU directive 89/429/EEC. The energy content of polyethylene is similar to that of the oil from which it is derived⁴.

Landfill has been the most common means of waste disposal in the UK for many years, largely due its low cost and at one time, the ready supply of large holes left behind from quarrying. However, the available landfill capacity is nearly all gone and concerns over the production of methane (a potent greenhouse gas) among other exudates from the sites has led to the Landfill Directive 99/31/EC which aims to reduce the amount of biodegradable waste going to landfill to 35% of the 1995 total by 2020.

2 Conclusions and interpretation

The focus of this report is on the environmental impact of oxo-degradable plastics in the end-of-life phase of the life cycle. Hence the conclusions from this report will concentrate on the end-of-life scenarios under the headings of degradation and biodegradation, bio-accumulation, toxicological impact, recycling, littering and landfill.

However, before focussing on end-of-life issues, it is worth summarising the evidence from the limited number of Life Cycle Analysis (LCA) studies that consider the environmental impacts of the production and use phases of oxo-degradable products.

2.1 Production and in-use phase

It is concluded that oxo-degradable polyethylene (PE) bags have the same effect on greenhouse gas emissions and on depletion of resources (i.e. oil depletion) as do conventional single-use polyethylene bags. (Section 4.1.5 and Annex A6). Hence, in the production and use phases of the life-cycle, oxo-degradable PE bags are not considered to have a significantly better or worse environmental impact than conventional single-use PE bags. The reason for this is that, during the production and use phases, by far the largest contributing factor to the environmental impact is the energy and oil used in the production of ethylene and its conversion to polyethylene.

In cases where the bag is being re-used, as in the 'bag for life', then the LCA study⁵ concluded that the oxo-degradable bag and the single-use bag both have a more negative impact than the 'bag for life'.

During the use phase of the PE bags, it should be noted that the fact that they are degradable limits the re-use of oxo-degradable bags. For example, the bags will fragment into small pieces and are therefore not suitable for storing items in the home over timescales in excess of one to two years.

Another point to make regarding the LCA of oxo-degradable bags is that because polyethylene is derived from oil, then, when these bags degrade to CO₂, they are releasing fossil carbon into the atmosphere. Hence they have a more negative environmental impact during this phase of the life cycle compared with disposable bags made from biopolymers, which are derived from renewable biomass sources⁶.

The oxo-degradable additive masterbatches are added at relatively low levels (usually 1 – 5 weight %) and of this only a fraction is the active ingredient (transition metal compound). The actual level of transition metal compound added to the end-product will vary according to the anticipated environmental conditions and the required time to degradation of the product. This information is not disclosed by the additive producers, but from examination of the patent literature^{7,8} and discussion with stakeholders (Annex C) it is estimated to be between 0.01 and 0.5 weight %. Given that the additives are used in very small amounts and are not considered harmful (see section 2.3 on toxicity below) it has not been found that these additives have a negative environmental impact in the production and use phase of the product life-cycle.

The key difference between oxo-degradable plastics and non degradable conventional plastics is in the disposal or end of life. Thus the effects at the 'end of life' are described in detail below.

2.2 Degradation and Bio-degradation

The most important parts of the study are the questions of the time scale over which oxo-degradables degrade and the extent to which they are biodegradable.

According to the additive producers, the time scale over which these materials degrade can be tailored according to the amount of additive in the formulation, particularly the active ingredient. Tests carried out under controlled conditions show this to be the case. However, the exact environment in which the product may end-up cannot be controlled, and so specific claims as to the time and extent of degradability cannot be justified. From discussion with stakeholders, it is suggested that degradation to small plastic fragments in the UK usually takes somewhere in the range of 2 to 5 years (section 4.3.1).

There is no question that oxo-degradable products do degrade and fragment when exposed to sunlight and/or heat for an extended period of time. The mechanism by which this happens is well researched and reported⁹(also Annex A). There is a complex series of chemical reactions in which the long chains of polyethylene molecules are broken down into shorter lengths by the action of oxygen, ultra-violet light and/or heat and this process is catalysed and accelerated by the transition metal compounds. The resulting material becomes brittle and will disintegrate into small fragments.

Much more questionable is whether these small fragments can be colonised and assimilated by microbes and therefore be described as biodegradable.

Conversion of the polymer to carbon dioxide (CO₂) is the most direct measurement of biodegradation. Therefore studies based on CO₂ evolution give a much more reliable indication of biodegradability rather than those based on, for example, weight loss measurements or images showing that the surface of the plastic has been colonised by micro-organisms. From the peer-reviewed literature, there were a lot of articles investigating the chemical changes that take place in artificially weathered oxo-degradable PE, which is then incubated in soil or exposed to cultures of specific bacteria. Some studies¹⁰⁻¹³ investigated the growth of selected bacteria and fungi on previously degraded oxo-degradable polyethylene, where it was the only source of carbon. Very few studies¹⁴⁻¹⁸ measured the extent to which the degraded polymer was converted by micro-organisms to carbon dioxide. (See results in section 4.1 and also Annex A1).

In these studies the oxo-degradable plastic films are first exposed to artificial weathering conditions, either of ultra-violet light or of heat (70°C), to accelerate the degradation process before biodegradation studies are carried out. It is not clear to what extent such accelerated weathering regimes correspond to or can be correlated with the conditions actually experienced in the environment. For this reason it is difficult to draw conclusions from these studies about the degree and timeframes for biodegradation of oxo-degradable plastics in the natural environment.

There is limited evidence from published research work, sponsored by the producers, that previously degraded material can be converted to carbon dioxide after burial in soil. For example, the work of Chiellini and Corti¹⁹ has shown conversion of about 50% of the material to carbon dioxide, when oxo-degradable polyethylene samples were buried in the soil for a relatively long period of time (550 days). The samples had been subjected to thermal treatment to initiate the degradation process prior to the biodegradation study. (See discussion in section 4.1.1 and Annex A2.1).

Contrary to these results, an international study funded by the European Commission using a standard biodegradation test (ASTM D5988-96) reported that after a year the oxo-degradable polyethylene had only converted to 15% carbon dioxide. This study by Feuilloley et al¹⁷ concluded that the oxo-degradable polyethylene mulch films underwent a very low degree of biodegradation in the standard tests. They also cited evidence of cross-linking between the molecular chains in the degraded polyethylene that may lead to fragments that can persist in the soil. This work is considered highly robust because it was part of an international programme using a number of standard test methods. (See section 4.1.1 and Annex A2.1).

Another independent study²⁰ carried out on behalf of the California Integrated Waste Management Board found that according to the biodegradation standard, ASTM D5338, the conversion of oxo-degradable plastic to carbon dioxide was about 2% over a 45 day test period compared with over 60% conversion for biodegradable plastics, such as polylactic acid. This study is regarded as highly robust: the experiments were run in triplicate and positive and negative controls were also run to ensure that the test system was valid. Moreover, trials in three commercial composting facilities that produce compost for sale to the public all reported that oxo-degradable plastic bags did not show any signs of degradation in timeframes of 120, 170 and 180 days. (See section 4.2.1 and Annex B1).

After reviewing a large body of published literature (sections 4.1 and 4.2), it has been concluded that studies carried out according to international standards EN13432 and ASTM D6400 show that oxo-degradables cannot be described as compostable and to describe them as biodegradable is likely to be confusing to consumers, over the most appropriate disposal routes for these materials.

This so called 'biodegradation' of oxo-degradable plastics is of particular concern to the organics recyclers, who are in the business of making and selling compost. The presence of contamination in the form of fragments of degraded plastic will adversely affect the quality and saleability of their product. Their experience of oxo-degradables is that they do not compost in industrial composting facilities. Such companies only want materials that are compostable according to the standard EN13432 to be allowed into the composting stream (section 4.3.1). In fact all stakeholders accept that oxo-degradable plastics do not pass the EN13432 compostability standard and, indeed, oxo-degradables are not claimed to be compostable. There is, however, concern among the composters that an alternative composting or biodegradation standard may be put forward in the future, which oxo-degradable plastics would be able to pass. This would then result in oxo-degradable material entering the composting stream. (Annex C6.1).

2.3 Bio-accumulation of Plastic Fragments in the Environment

An area of uncertainty is the fate of plastic fragments that remain in the soil. These are regarded as beneficial by the producers because they are claimed to add to the content of humus in the soil². However, there is a lack of evidence about the environmental impact of oxo-degradable plastic fragments in the soil and a number of concerns have been raised. For example, these fragments might act to concentrate pesticide residues in the soil²¹. It is possible that they may become ingested by earthworms, other insects, birds or animals. Alternatively, they may enter watercourses and become ingested by fish or birds. It is also possible that they may find their way into the marine environment and become ingested by marine organisms²². There are also concerns that degraded fragments may become cross-linked and hence persist in the environment¹⁷. (See section 4.1.2).

No evidence was found in this study that oxo-degradable fragments have a harmful bioaccumulative effect but neither was there evidence that they do not. It was therefore concluded that this is a topic requiring more research.

2.4 Toxicological Impact

No evidence of a toxicological impact of oxo-degradables has been found in this literature review.

Research into the toxicological impact of oxo-degradable additives has been carried out by the University of California and also by the manufacturers of one additive (Section 4.2.3 and Annex B). The effect of compost derived from oxo-degradable polyethylene on the germination and growth of seeds from various plants was examined and no adverse effects were found. Both tests were carried out according to standard procedures (ISO 11269) and are therefore considered to be highly robust. No evidence was found of the toxicological impact on animals.

Concerns have been raised about release of 'heavy metals' from the oxo-degradable additives into the soil. The additive producers respond to this by saying that the metals used are transition metals (iron, nickel, cobalt and manganese) and are not "heavy" metals. Moreover, they are present in such small quantities that they will not significantly increase the concentrations of the metal ions already present in the soil. Their claims are supported with results from trials and calculations based on expected levels of usage. These claims seem reasonable and no evidence has been found in this study to dispute them. (Section 4.3.2).

2.5 Post Consumer Recycling

According to the producers and suppliers, oxo-degradables are claimed to be recyclable (i.e. capable of being recycled). This is strictly true in the sense that, even if degradation has started to take place, it is still possible to re-melt the polyethylene and re-process it together with other recycled material. However, there is an obvious concern from plastics recyclers that the presence of oxo-degradables in the recycling stream will have an adverse effect on the quality and usability of the product. It is quite clear that the product will be more prone to degradation, which will be particularly damaging for long-life applications such as membranes used in construction, and medium-life applications, such as garden furniture. The additive producers suggest that stabilisers can be added to offset the effect of the oxo-degradable additive, but the problem then arises as to the quantity of stabiliser required. Also, if the oxo-degradable plastic has already undergone degradation, this process will not be reversed by addition of stabiliser. It has been concluded on this basis that it is unreasonable to claim that oxo-degradable plastics are recyclable in existing recycling streams. (See section 4.3.4).

In the course of this study, it was difficult to find evidence of the impact of oxo-degradables on the recycling stream. At present there seems to be very little post-consumer recycling of the sort of plastic film products where oxo-degradable plastics are usually used. This is mainly because such material is difficult to collect, is generally of poor quality and is therefore not economically viable for recyclers. Hence, at present, any deleterious effect is limited. (Annex C6.4).

There is another more far-reaching concern, that now that this technology is being developed for use in other plastics, such as polyethylene terephthalate (PET), and for other applications, such as bottles, then there is more potential for a negative impact on the quality of recycled plastic from existing recycling schemes^{23, 24}.

2.6 Littering

Littering is an aspect about which it was difficult to acquire robust evidence. The oxo-degradable producers maintain that their products are a solution to the littering problem because oxo-degradable packaging will eventually degrade and then biodegrade. Some retailers are concerned that oxo-degradable carrier bags are less likely to be re-used by the public and it is much better to promote the concept of good quality multi-use carrier bags. There is also concern that oxo-degradable carrier bags may promote littering if the public are told that these bags are biodegradable.

There was not found to be any robust evidence that the type of carrier bag (oxo-degradable or not) affects the way in which they are disposed of by the public. The perceived amount of litter may be reduced by the use of oxo-degradables because after embrittlement takes place the bags become fragmented and disperse. Whether this is actually beneficial or harmful for the environment depends on what happens to the plastic fragments. As discussed in section 2.2 above, there is very little robust evidence for the fate of oxo-degradable fragments and this is an area identified as requiring further research. Nevertheless, as the plastics will not degrade for 2-5 years the plastics will still cause litter within this timeframe.

2.7 Landfill

There is only a limited amount of information about what, if anything, happens to oxo-degradable plastics in landfill sites. Two reports are discussed in section 4.2.1 and in Annex B1 and Annex B2. Results from these are summarised briefly below.

A landfill study carried out by the University of California²⁰ (Annex B1) has reported that oxo-degradable PE did not undergo anaerobic biodegradation (biodegradation in the absence of air) during the study period of 43 days. A control sample of paper did biodegrade under the same anaerobic conditions to produce methane gas. This supports claims from the producers of oxo-degradables that these products will not emit methane in anaerobic conditions in landfill sites (Annex B5). However, 43 days is a rather short time and further evidence would be required to confirm that oxo-degradable PE will not emit methane in landfill sites.

A second landfill study is reported in Annex B2. This relates to aerobic conditions i.e. where air is available near the surface of the landfill. There is evidence from this study that oxo-degradable PE will continue to degrade in a landfill site where sufficient oxygen is available. However, there are some unexplained contrary results in this study and so it is regarded to be of low robustness and there is some doubt over the general applicability of the findings.

2.8 Conclusions

The overall conclusion of this review is that incorporation of additives into petroleum-based plastics that cause those plastics to undergo accelerated degradation does not improve their environmental impact and potentially gives rise to certain negative effects.

2.8.1 *Degradation and biodegradation*

- a) The length of time to degradation of oxo-degradable plastic cannot be predicted accurately because it depends so much on the environmental conditions. It is suggested that oxo-degradable plastics left in the open environment in the UK degrade to small fragments in 2 to 5 years.
- b) Biodegradation of oxo-degradable plastics can only occur after they have fragmented and then proceeds very slowly, for example, at a rate many times slower than that of a compostable plastic.
- c) Oxo-degradable plastics are not compostable, according to standards EN13432 and ASTM 6400. Oxo-degradable plastics should not be included in waste going for composting, because the plastic fragments remaining after the composting process will adversely affect the quality and saleability of the compost. It is thought that labelling the oxo-degradable plastics as biodegradable may lead to confusion on the part of the consumer and possible contamination of the composting waste-stream with oxo-degradable plastics.
- d) The fact that the term “biodegradable” can be applied to materials with extremely widely differing rates of biodegradation demonstrates that the term is virtually meaningless unless the rates of biodegradation and conditions under which it is measured are specified, preferably with reference to a widely recognised standard.

2.8.2 *Bio-accumulation of plastic fragments in the environment*

The fate of plastic fragments that remain in the soil is an area of uncertainty. Although these are regarded as beneficial by the producers, concerns have been raised that these particles of plastic may be ingested by insects, birds, animals or fish. No evidence was found in this study that oxo-degradable fragments have a harmful bio-accumulative effect but neither was there evidence that they do not.

2.8.3 *Toxicological Impact*

No evidence of a toxicological impact of oxo-degradable additives was found in this literature review. It is concluded that the transition metals used are present in such small amounts that they will not significantly increase the concentrations naturally present in the soil at expected levels of usage.

2.8.4 Re-use

The fact that they are degradable limits the re-use of oxo-degradable bags: they are unsuitable for storing items for an extended length of time.

2.8.5 Recycling

Oxo-degradable plastics are not suitable for recycling with main-stream plastics. The recycle will contain oxo-degradable additives that will render the product more susceptible to degradation. Although the additive producers suggest that stabilisers can be added to protect against the oxo-degradable additives, it is problematic to determine how much stabiliser needs to be added and to what extent the oxo-degradable plastic has already degraded.

2.8.6 Disposal

The potential for problems to be caused by incorrect disposal of oxo-degradable plastics means that any packaging should be clearly labelled with the appropriate means of disposal. Life cycle analysis suggests that the best means of disposal for oxo-degradable plastics is incineration. If incineration is not available then landfill is the next best option.

2.9 Recommendations

The recommendations regarding oxo-degradable plastics made on the basis of all the evidence reviewed in this study from the peer-reviewed literature, non-peer-reviewed literature (reports and websites) and also from stakeholder interviews are given below.

- The term 'biodegradable' does not indicate the environment or timescale required for biodegradation to occur and is therefore problematic for labelling packaging.

There are two possible solutions to this:-

- (i) One solution is that if the term 'biodegradable' is used then it is necessary to define the disposal environment, extent of biodegradation in a short given time period or the time taken to complete biodegradation.
 - (ii) The other solution is not to use the term 'biodegradable' for labelling packaging at all, but to only label with instructions on the means of disposal.
- The fate of oxo-degradable plastic after it has fragmented to a fine powder is not clear. Therefore it is recommended that further research is carried out to determine whether complete degradation to carbon dioxide and water is achieved, and if so, over what time scale. If the fine particles are found to persist in the environment for a long period of time, the potential for harm is such that research should be carried out to determine the effect of the particles on plants, invertebrates and animals.
 - The uncertainties surrounding the effect of oxo-degradable plastics on the conventional plastics recycling process means that the safest solution would be to keep oxo-degradable plastics out of mainstream plastics recycling processes.

3 Methods and approach

3.1 Literature Reviews

An extensive survey of the peer-reviewed, scientific literature was carried out on oxo-degradable plastics. Literature searches were carried out using the following databases: CSA, Web of Science, Esp@ce Patent Database and Google Scholar. Initial search terms were selected to give as wide a spread of results as possible. From the initial results, more selective terms were introduced to give a more manageable list of 'hits' from which to work. From these results, working bibliographies were selected, containing all the articles to be analysed for the report.

Papers from the peer-reviewed literature are discussed in the Results Section 4.1 and in Annex A.

Other literature reviewed in this report is described as 'non-peer reviewed'. This was found from websites and other sources in the public domain. This series of studies is reviewed in the Results Section 4.2 and in Annexes B1 – B5. These mainly take the form of specially commissioned studies and are an important source of information.

3.2 Stakeholder views

The views of various stakeholders were obtained by interviews carried out face-to-face, over the telephone or via e-mail. Stakeholders were encouraged to provide evidence for their views where possible and were asked to justify their opinions. Some stakeholders had significant amounts of information on their websites and this provided a good source of material.

The nature of the questions and topics of conversation varied with the type of stakeholder and some examples are given below. It was made clear that the information would be used to prepare a report that would be widely available and probably published on the DEFRA Website.

3.2.1 *Producers of Additives*

Seven producers of oxo-degradable additives were contacted and asked:-

1. To provide as much information as possible about the content of the additives
2. Their opinion on the effect of the degradation products of an oxo-degradable plastic on the environment
3. How long they thought oxo-degradable plastics would persist before breaking down in the environment
4. Whether they thought oxo-degradable plastics were biodegradable
5. What they believed the effect would be if oxo-degradable plastics were added to a plastics recycling stream.
6. Where they believed the use of oxo-degradable plastics lay in relation to recycling of conventional plastics and the use of biopolymers.

3.2.2 Retailers

Eight major retailers were contacted for their views on oxo-degradable plastics, including both those who use and those who do not use oxo-degradable plastics.

Retailers were asked about the following:-

1. On what basis they made their choice to either use or not use oxo-degradable packaging? (e.g. survey of customer opinion, result of their own research into best environmental option).
2. Their opinions of relative advantages/disadvantages of oxo-degradable plastics compared with other approaches – e.g. recycling, re-usable bags.
3. Whether they used oxo-degradable packaging and if so, for what type of product (e.g. carrier bags, fresh food packaging).
4. If they used oxo-degradable packaging, whether they labelled it as such and whether they gave instructions to the consumer on how to dispose of it.
5. Whether they had any feedback from customers or others regarding oxo-degradable plastics for example, with regard to littering.

3.2.3 Business Organisations

The organisations contacted were as follows:-

- The British Plastics Federation (BPF) – Biobased and Degradable Plastics Group. Contact was made with individual members of this group.
- British Plastics Recycling Council
- Re-coup
- The Packaging and Films Association (PAFA)
- Plastics Consultancy Network (via BPF) for information on processing of oxo-degradable polyethylene.

The organisations were asked for their opinions on the environmental effects of oxo-degradable plastics and their possible impact on recycling of plastics.

3.2.4 Agricultural users

The National Farmers Union was contacted to find their views on the application of oxo-degradable plastics in agricultural applications such as mulch.

They were asked to what extent the oxo-degradable plastics broke down and whether there was any evident build-up of plastic particles in the soil. They were also asked if they knew of any effects on plant growth that could be attributed to the oxo-degradable plastics.

3.2.5 Organics recyclers

The Association for Organics Recycling (formerly The Composting Association) and an organics recycling company were asked for their views on how they thought oxo-degradable plastics affected their sector.

They were asked if:-

1. There were policies regarding the admission of oxo-degradable plastics to composting facilities.
2. They had observed that oxo-degradable plastics broke down during composting
3. Oxo-degradable plastics adversely affect the composting process

4 Results

4.1 Results of the Peer-reviewed Literature Survey

4.1.1 Biodegradability

There are a limited number of reviews covering the subject of biodegradable plastics or oxo-degradable polyethylenes in particular. The review by Kyrikou²⁵ addresses the question as to what is an acceptable timescale for biodegradation and how it should be measured. A paper given by Narayan²¹ sets out the case for the measurement of evolved carbon dioxide when the polyethylene is incubated in a soil or compost as the true measure of biodegradability. In the same review, Narayan, maintains that claims that a plastic will ‘eventually degrade’ without specifying a timescale are unacceptable:

“Specifying time to complete biodegradation or put in a better way time to complete microbial assimilation of the test plastic in the selected disposal environment is an essential requirement – so stating that it will eventually biodegrade or it is partially biodegradable or it is degradable is not acceptable.”²¹

In view of the above, the most robust data for the purpose of this survey would satisfy the following conditions:

1. The tests were performed according to international or national standards defined by standards bodies such as the International Standards Organisation (ISO), the American Society for Testing and Materials (ASTM) and the European Organisation for Standardisation (EN).
2. The tests were carried out with sufficient replicates to enable some estimate of the variability to be made.
3. The methods and test results are published in peer-reviewed journals, where the article has been read and commented on by experts in the subject who have then approved that the article be published.

There is very little peer-reviewed literature that presents data on the biodegradation of oxo-degradable polyethylene, where the biodegradation has been followed by measuring the carbon dioxide released by the polymer. In these tests, the sample would be incubated in either soil or compost in a closed vessel through which air is passed. The exhaust air would be sampled for carbon dioxide. Where no biodegradable material is present, the carbon dioxide emissions would be low and this would be considered the ‘background’ or ‘control’ level. Where a biodegradable material is present, the carbon dioxide emissions would be higher and the difference between this higher value and the control represents the carbon dioxide produced as a result of biodegradation of the sample. It is important to have two other controls: a positive control, which is a sample of material that would be definitely known to degrade, such as cellulose and a negative control which would consist of a material that would not be expected to degrade. Polyethylene is often used as a negative control.

Although many reports in the peer-reviewed literature include 'biodegradation' in the title, the meaning of the term is flexible. For example, some studies^{26, 27} use the term to refer to evidence of microbial growth on the surface of the polymer whereas other studies use the term to indicate that the PE samples were subjected to a biotic environment (soil, compost) as part of the experimental procedure²⁸.

It is claimed by the manufacturers of oxo-degradable polyethylene that this material becomes biodegradable after a suitable period of exposure to ultraviolet light, or elevated temperature. The former treatment may be referred to as 'photodegraded' or 'photo-oxidised' while the latter may be referred to as 'thermally activated' or 'thermally oxidised'.

In a report published in 1994²⁹, two samples of oxo-degradable polyethylene from different manufacturers were exposed to sunlight for 6 and 12 weeks before being subjected to soil burial for 3 months during which the evolved carbon dioxide was measured. The exposure was carried out to ASTM D1346-75, which stipulates the conditions for testing the outdoor weathering of plastics. This is the only account of a test where the materials were subjected to an environmental exposure to ultraviolet light before the soil burial. In all other studies reviewed in this report, the material had been exposed to ultraviolet light in laboratory conditions. The authors calculated how much of the oxo-degradable polyethylene carbon had been converted to carbon dioxide and found values of 3.5% and 4.5% for the two samples. This was for samples that had been exposed for 6 weeks. When the samples were exposed for 12 weeks, the amount of conversion were lower, being 2.9% and 1.5% respectively. This result would suggest that increasing the exposure to sunlight had rendered the samples less biodegradable rather than more.

There is only one report that tests the biodegradation of an oxo-degradable polyethylene by a standard method. This was conducted by Feuilloley et. al.¹⁷. In this study, three materials were tested: Mater-Bi (a blend of starch and a biodegradable polymer derived from petroleum); Ecoflex (a compostable synthetic polymer) and Actimais (polyethylene with a pro-oxidant additive). These materials were tested by ten different standard ASTM, ISO and EN methods. Further details of these tests are given in Annex A.

The ASTM5988-96 test measures the carbon dioxide evolved by the test material when incubated in real soil. In this test, the oxo-degradable polyethylene sample showed a biodegradation of 15% after 350 days of incubation, whereas the paper control sample showed a biodegradation of 90%. Furthermore, the authors found that the evolution of carbon dioxide by the oxo-degradable polyethylene reached a maximum after 200 days and did not increase thereafter, in other words, a plateau was reached before seven months. In eight of the remaining nine tests, the biodegradation of oxo-degradable polyethylene varied from negative to a maximum of 1.8%. The exception was the "Agricultural soil test" where the sample was buried in real agricultural soil for 330 days. In this test the apparent biodegradation was 90% although, as the authors commented, the assessment is made by visual inspection and it was found to be possible to extract significant quantities of microscopic fragments of undegraded oxo-degradable polyethylene from the soil after the test. The implication of these fragments is discussed later in this section under the heading 'crosslinking'.

For comparison, the biodegradation of Mater-Bi was 75-88% and that of Ecoflex was 5-95% in all ten of the tests under the different standard methods.

In a report published in 2003, Chiellini & Corti¹⁹ used a modified test to measure the ultimate biodegradability of natural, synthetic and semi-synthetic polymeric materials in soil and mature compost. The original test was intended to measure the biodegradability of pesticides in soil. In the modified version, soil and compost samples were diluted with perlite

(an inert material often used in commercial compost) to ensure optimal conditions for microbial growth. In this study, the material was incubated in a closed vessel for 550 days and the carbon dioxide produced was measured. It is notable in this account that there is no description of the thermal treatment of the test specimen before the incubation although in the results section, the graph showing the carbon dioxide evolution refers to the samples as “thermally oxidized LDPE”. Thus the implication is that the samples had been pre-treated by heating in order to activate the additive, but it is not known at what temperature and for how long. The oxo-degradable polyethylene was tested at two concentrations: 22 and 45 mg of sample per gram of soil. These are referred to as ‘replicates’ by the authors despite the twofold difference in concentration.

In biodegradation studies, there is very often a delay in the start of carbon dioxide evolution which is referred to as the ‘lag phase’ and is usually explained as the time taken for the microbial population to ‘adapt’ to the new material, or substrate. In the modified test of Chiellini and Corti, the biodegradation of the oxo-degradable polyethylene did not commence until after 150 days, whereas that of the paper control was less than 10 days. The test ran for 567 days after which the biodegradation of the lower concentration of sample was 59% and that of the higher concentration was 47%. It is difficult to say how these results can be translated to a real-life usage of the materials because of the lack of information as to the thermal pre-treatment. In other accounts, the typical temperatures used for thermal activation are in the range 50°C to 70°C and such temperatures are unlikely to be obtained in fields in the UK.

Although there are very few published studies of the biodegradation of degradable polyethylene, the author E.Chiellini has produced a number of publications since 2007 and this could be an indication of increased activity in this field. However, these studies are complicated by the fact that the polyethylene is extracted with solvents after thermal activation and the fractions are tested. Thus, although a biodegradation of 60% is claimed for oxo-degradable polyethylene in one study¹⁶, this is actually for a low molecular weight fraction and is therefore not representative of the whole material.

There are some reports of studies where the test material was incubated in microbial cultures to look for evidence of degradation. These were not true biodegradation tests where evolved carbon dioxide was measured. The results of these studies suggest that while microorganisms can colonise the surface of degradable polyethylene and can initially multiply, the growth rate soon drops. This was explained by suggesting that the microorganisms were capable of feeding on the easily-degraded portion of the polyethylene, but that this is soon exhausted and the growth rate drops as this supply is depleted¹¹.

In conclusion, the peer-reviewed evidence based on standard methods suggests that the biodegradation of oxo-degradable polyethylene is no more than 15% after 350 days. Although a higher rate can be achieved this requires thermal activation and it is uncertain as to exactly what temperature is required to do this. Even with thermal activation, there is a significant delay before the degradation commences.

4.1.2 Evidence for cross-linking of oxo-degradable polyethylene fragments

Cross-linking is a chemical process in which long-chain molecules such as polyethylene can join “side by side” instead of “end to end”. The result is that a molecule which starts as a straight chain can become branched. If this reaction continues, the branched molecule becomes less easily broken down and also less soluble. Thus polyethylene is soluble in certain organic liquids, but when it becomes cross-linked, it becomes insoluble and instead swells in the liquid without dissolving. The oxidative degradation mechanism proposed by

Scott and others includes the possibility that polymer fragments can recombine and cross-link³⁰. The consequence of cross-linking between the molecular chains in the degraded polyethylene is that it may lead to fragments persisting in the soil.

Feuilloley et. al.¹⁷ retrieved polyethylene fragments from soil that had an oxo-degradable polyethylene mulch applied 2 years previously. Fragments of 5-70um size were recovered but not quantified other than to be described as 'numerous'. The authors suggested that the low solubility in hot xylene was strong evidence that the polyethylene in these fragments was cross-linked, possibly as a result of the degradation process. This author suggested that the implications of crosslinking of the degrading polyethylene were rarely discussed and that the extent may well be underestimated.

Further evidence for crosslinking comes from a study conducted in 1994 where photodegradable polyethylene samples were exposed to sunlight for 6 and 12 weeks before being subjected to a biodegradation assay²⁹. The results indicated that the biodegradation of the 12-week sample was significantly lower than that of the unexposed sample and the 6-week sample, suggesting that the longer exposure had made the material less biodegradable rather than more. Other workers³⁰ have suggested that the extent of cross-linking depends on the film thickness, such that thicker films are more likely to crosslink than thinner films and that thermal treatments are also likely to lead to crosslinking reactions. In this study, crosslinking was found to occur at 60°C, which is the temperature achieved in the composting process.

4.1.3 Bioaccumulation

4.1.3.1 Evidence of Accumulation of Pro-oxidant Metals in Plants

There are very few reports dealing with the possibility of bio-accumulation of pro-oxidant metals by plants, after oxo-degradable plastics have been applied. However, Wolfe et. al.³¹ attempted to mimic the cumulative effect on a soil of applying a oxo-degradable mulch annually for thirty years. They added a single amount of photodegraded polyethylene that represented thirty years worth of annual use of degradable mulch film. In this context, 'photodegraded' means that the plastic film had been exposed to ultraviolet light in order to degrade the polyethylene.

The authors looked for two substances: the nickel, which is a metal used in the oxo-degradable formulation and a substance called dithiocarbamate which is used to carry the nickel in the formulation. The authors did not detect any dithiocarbamate residues in either the harvested crop or soil samples. There were no consistent differences in the amounts of nickel between the treated or the control crops and the treated soil and control soil samples.

The material added in this study was photodegraded but had not necessarily been composted or exposed to soil. This means that although the material had undergone degradation, this was not by the action of soil microorganisms and it is still unknown therefore, how the biodegraded material would act in this situation. It is also unknown how such a system would respond to a repeated annual input of degradable polyethylene.

4.1.3.2 Evidence for Accumulation of oxo-degradable polyethylene residues in organisms

There are no reports of this in the literature. Although it has been shown that PE fragments of size 5-70um persist in the soil¹⁷ and are therefore of a size that could possibly be ingested by earthworms, this is an area where further research needs to be done.

4.1.3.3 Evidence for Concentration of Pollutants by oxo-degradable polyethylene Residues

There is no direct evidence specific to the accumulation of pollutants by oxo-degradable polyethylene residues, although several authors have alluded to the possibility with plastics in general³²³³

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There is one study on the accumulation of marine pollutants by polypropylene resin pellets (so-called 'nurdles')³⁴. This study found that polychlorinated biphenyls (PCB), the pesticide DDE and nonyl phenols were concentrated from sea water by polypropylene pellets by a factor of x100,000 to x1,000,000. There are no equivalent terrestrial-based studies on this area.

4.1.4 Toxicological Impact

A study on the effects of degradable municipal waste bags on windrow composting did not show any evidence of increase in transition metal content (copper & cobalt) of compost³⁵. However, in this report it was noted that one effect of the presence of shreds of waste bags in the compost windrows was that the free drainage of water through the soil was impeded by the plastic shreds. The composting process is very sensitive to moisture content and slows down in waterlogged material.

Environmental toxicity of a substance is assessed by standard tests in which the substance is introduced to the environment of selected plant and animal species judged to be sensitive to pollutants. The test plants used are cress and oat lentil while the earthworm is used as a sensitive indicator of the toxic effects of substances likely to end up in soil. For assessment of toxicity to freshwater organisms, the microscopic organism *Daphnia* is used. There is no published peer-reviewed evidence on the toxicity of compost to the organisms listed in the standard tests (*Daphnia*, earthworm, cress, oat lentil) although one article refers to these tests without giving any further details.

Very little peer-reviewed published work has been done to assess the toxicity of the oxo-degradable additives to plant, soil and freshwater organisms.

There is only one peer-reviewed report that assesses the toxicity to plants of compost made from oxo-degradable polyethylene³⁵ and this report did not find any toxic effect on tomato plants.

Food Toxicity

This review has not revealed any direct toxicity of degradable polyolefins. Private tests carried out by Rapra on behalf of a producer of oxo-degradable plastics (see Annex B5) concluded that the materials tested passed the Food Migration standards stipulated by, for example, Current European Directives 2004/19/EC².

² 2004/19/EC Commission Directive of 1 March 2004 amending Directive 2002/72/EC relating to plastic materials and articles intended to come into contact with foodstuffs

4.1.5 Production and In-use Phase

To date, there is one full Life Cycle Assessment carried out that includes oxo-degradable polyethylene bags and compares them to other polymers including poly(lactic acid) and non-degradable polyethylene⁵. The assessment indicated that the impacts at the production and in-use phase of oxo-degradable polyethylene were similar to those of non-degradable polyethylene. The most serious negative impact of oxo-degradable polyethylene was on the depletion of resources of oil, coal and natural gas.

In cases where the bag is re-used, as in the 'bag for life', then the LCA study⁵ concluded that the oxo-degradable bag and the single-use bag both have a more negative impact than the 'bag for life'. The fact that they are degradable limits the re-use of oxo-degradable bags. For example, the bags will fragment into small pieces and are therefore not suitable for storing items in the home over timescales in excess of one to two years.

Nevertheless, the key difference between oxo-degradable plastics and non-degradable polyethelene is in its disposal, or 'end of life' – thus the focus of this review.

4.2 Non-Peer-Reviewed Literature

The non peer-reviewed literature surveyed in this report consists mainly of material presented by oxo-degradable polyethylene additive manufacturers, and often available on their websites. Most of the literature is in the form of technical reports which were commissioned by the manufacturers of the additives and prepared by independent consultants.

The five sources of information listed below represent a balanced view of what is available in non-peer reviewed literature on the subject of the environmental impact of oxo-degradable plastics. Each of the documents has been analysed in detail in Annex B and the main conclusions from the analysis are discussed in the following sections:

1. A Performance Evaluation carried out by the University of California on behalf of the Integrated Waste Management Board of the State of California²⁰ (Annex B1)
2. An Evaluation of Degradability carried out by MJ Carter Associates³⁶. This was based on a landfill trial located in Birmingham, UK (Annex B2).
3. A report on a windrow composting trial carried out at Vienna Neustadt in Austria. (Annex B3).
4. A report on a windrow composting trial in Wisconsin US.(Annex B4).
5. A list of claims made on a company website, which refers to several technical reports, which were then obtained and examined in detail. (Annex B5).

4.2.1 Degradation and Biodegradation

One of the issues concerning the degradation of oxo-degradable plastics is that it depends very much on environmental conditions. Most oxo-degradable plastics would be expected to end up in landfill sites, so it is clearly important to understand the type of degradation that occurs in this environment.

A landfill-based trial was conducted at a site in Birmingham (UK) over 14 months from January 2001 to March 2002³⁶. The assessment was based on physical tests rather than appearance, however, the numeric data from this study were not available. The main test was based on the melt flow index: this is a value that increases as a polymer degrades so that a high value is taken to indicate that degradation has taken place. This trial also focused on whether a critical value of 30°C was reached in the landfill site during the testing period. It was found that the critical temperature (30°C) was not reached until four months into the trial when one temperature probe registered this temperature. After ten months into the trial (November), ten of the probes registered the critical temperature. The molecular weight of one recovered oxo-degradable polyethylene sample was measured and it was found that the molecular weight had dropped to below the 5000 value required for biodegradation to take place. The melt flow index results indicated that the oxo-degradable polyethylene material had degraded significantly ten months into the trial, because the melt flow index had increased by tenfold. However, fourteen months into the trial, the melt flow of recovered samples had dropped and no explanation was given for this. Furthermore, although it was noted that four out of nine recovered oxo-degradable polyethylene samples gave melt flow index values that were higher than the control materials, the values of the other five samples were not discussed. The implication is that they were either equal to the control or greater. The results of this trial do provide evidence for some molecular level

degradation in landfill but the unexplained contrary results cast some doubt over the certainty and broad applicability of the conclusions.

Another study that may relate to the deeper levels of a landfill site, where anaerobic conditions are expected, was carried out by the University of California²⁰ (Annex B1). From the results it was concluded that oxo-degradable polyethylene did not undergo anaerobic biodegradation (biodegradation in the absence of air) after 43 days, whereas a control experiment using paper showed 6% anaerobic degradation (thus confirming the validity of the test). This result supports claim 11 in Annex B5 that oxo-degradable additives will not emit methane in anaerobic conditions.

Oxo-degradable plastic additive manufacturers and suppliers generally claim that oxo-degradable plastics are bio-degradable, some even naming them “oxo-biodegradable”. Claims of biodegradability are usually supported by reference to the results of experimental studies. The credibility of the claims depends strongly on the relevance of the experimental conditions, the use of controls, the robustness with which the results were analysed and whether results have only been selectively referred to. An example of a typical claim is given in claim 4 in Annex B5, where it is implied that the product will comply with a standard biodegradation test (ASTM6954-04). The basis of the claim is that the molecular weight of the material has been reduced by heat treatment (70°C) to below a critical value of 5,000, the value required for biodegradation to commence. However the report cited in support of this claim described what happened to three samples³⁷. One sample did indeed reach the value of 5,000 after 7 days at 70°C, however another sample heated for 9 days had a molecular weight greater than 5000 while another sample had a molecular weight of 12,000 after treatment with ultraviolet light for 7 days. There was therefore considerable variability in the behaviour of the samples and as no replicate measurements were performed, the evidence is of low robustness. A further document cited in support of this claim appears to have been prepared by an independent investigator. This document presents microscope images showing that the surface of the samples had been colonised by microorganisms and suggests that some of the plastic mass had been removed as a result. The conclusion that the samples would “fully biodegrade” is based on these observations. It also appears from this second report that the sample was tested for biodegradation by placing it in an outdoor fishpond. In view of this and the lack of replicate measurements or any statistical analysis, this evidence again is of low robustness.

A rare example of a more rigorous non-peer reviewed study is one carried out by the University of California²⁰, where biodegradation was measured by the level of conversion of the material to carbon dioxide (CO₂), according to ASTM D5338. The experiments were run in triplicate and positive and negative controls were also run to ensure that the test system was valid. The finding was that over 45 days, whereas the degradation of the cellulose control was greater than 70%, that of the oxo-degradable polyethylene sample was 2.2%, while the blank value for the compost alone was 1.7%. There are no other non peer-reviewed reports of similar experiments, but this result can be usefully compared to that published by Feuilloley et al.¹⁷, which was a peer-reviewed study.

A special case of biodegradation is composting, a significant distinction because it is a commercially important process. Most oxo-degradable plastics are not claimed to be compostable. For example, the makers of one additive state on their company website that their “oxo-biodegradable plastics are not currently intended for composting” (see Annex B5). Lack of compostability was confirmed in a trial involving three municipal composting facilities in California²⁰ where the composting period ranged from 90 days to 180 days. It was concluded that the oxo-degradable polyethylene samples tested did not significantly degrade during the course of the trials. The conclusions were based on visual assessment of the samples and photographs of the materials before and after testing are shown in Annex B1.

4.2.2 Bioaccumulation

There is very little in the non peer-reviewed literature on bioaccumulation. This is to be expected as such tests are often expensive to run.

4.2.3 Toxicological Impact

The toxicological impact of the oxo-degradable additives has been assessed by various bodies by evaluating the effect of compost derived from oxo-degradable polyethylene on the germination of various plant seeds.

This has been done by the University of California²⁰ and also by one manufacturer³⁸, as asserted in claim 5 (Annex B5). Both tests were carried out according to standard procedures. The University of California found no evidence of toxicity to tomato, cucumber or cress seeds while the report cited in claim 5 (Annex B5) concluded that there were no adverse effects on either summer barley or cress and that the compost therefore met the requirements of EN13432. As these tests were performed in strict accordance with standard procedures with the required number of replicates, the evidence here is considered to be highly robust.

4.2.4 Recycling

No non peer-reviewed articles were found on the subject of the effect of oxo-degradable plastics on melt recycling of conventional plastics. The effect on the organics recycling (composting) process is discussed in the Degradation and Biodegradation section.

4.2.5 Production and In-use Phase

No non peer-reviewed evidence concerning life cycle analysis of oxo-degradable plastics was found.

4.3 Stakeholder Views

4.3.1 *Degradability and biodegradability*

There are two main areas of contention surrounding the degradability of oxo-degradable plastics. One is the time scale over which they degrade and the other is the extent to which they are biodegradable.

Some additive producers contend that the timescale of degradation can be quite closely controlled by tailoring the additive package for a particular application. Examples of results from studies may support this (see Annex A and Annex B), however, by their nature, these studies are under controlled conditions. In real life there is a wide range of environments that the plastic may pass through. Some additive producers accept this point and admit that it is difficult to predict the time of degradation because it is dependent upon the environmental conditions. Claims on packaging such as carrier bags, sometimes give a particular number of years by which time the plastic should have degraded. The claims indicate to the consumer a degree of certainty that is probably not justified considering the range of possible locations where the plastic may end up. The claimed degradation times are usually in the range of 2 to 5 years.

The uncertainty of the extent of degradation in different environments is illustrated in the conflicting views of what happens in landfill. Some stakeholders say that as landfill is an anaerobic environment, the oxo-degradable plastics will not degrade. However, others say that at the early stages of land-filling the environment is aerobic and at a relatively high temperature, so that oxo-degradable plastics will degrade.

There is little controversy about the early stage of degradation which leads to embrittlement of the plastic, followed by disintegration into smaller pieces. However, there is much disagreement about what happens next. The additive producers on the whole state that once the plastic has fragmented into a sufficiently fine powder it is then available as a substrate for organisms and is biodegradable, ultimately breaking down completely to carbon dioxide and water. Their assertion of biodegradability is made clear in the fact that some of these materials are even termed oxo-biodegradable. Many other stakeholders do not believe this claim but assume that the plastic remains in the environment essentially chemically unchanged but as a fine powder. The distinction between the two points of view becomes important when the fate of any plastic powder that persists for a long period in the environment is considered. The section on bio-accumulation (4.3.2) addresses this issue.

A very particular and commercially important form of biodegradability is compostability. There are many waste management companies that take in organic waste and process it to make compost that can then be sold. One concern of these composters is that of contamination of their input material by plastic of any kind, which might adversely affect the composting process and the resultant product. Such companies are keen that only materials that are compostable according to the standard EN13432 should be allowed into the composting stream. It is accepted by all stakeholders that oxo-degradable plastics do not pass this compostability standard and they are not generally claimed to be compostable. However, there is still unease among the composters that an alternative composting or biodegradation standard will be put forward that oxo-degradable plastics will pass and so open the door to this type of plastic entering the composting stream. The composters are very much against any such loosening of standards since their experience of oxo-

degradable plastics in composting systems is of incomplete degradation, which can lead to visible plastic remaining in the compost, adversely affecting its saleability. For their part, the producers of oxo-degradable plastics state that their objective is to ensure degradation and biodegradation in the open environment, rather than in industrial composting processes.

Another application where compostability has been an issue is in the use of agricultural mulch films. The main reason for using them in these applications is that they can be disposed of in-situ and need not be removed and disposed of. Citing their lack of compostability, the Environment Agency does not allow un-degraded oxo-degradable plastics to be returned to the soil by ploughing in. This prohibition, fundamentally limits the application of these materials and means that oxo-degradable mulch films have only been used in trials in the UK. The NFU suggests that degradable mulch films that can be ploughed in are of potential benefit to the farmer, avoiding the need for collection and disposal that can be both costly and potentially damaging to the environment. However, such films could only be used if they could be proved to be safe, to the satisfaction of the Environment Agency and if they could be proved to be effective in the field. Farmers would do not want to risk losing single farm subsidy payments by carrying out practices not approved by the Environment Agency. One producer of mulch films indicated that uncertainty about time to degradation would certainly limit the use in such applications.

4.3.2 Bio-accumulation

The additives used to make plastics oxo-degradable are usually metal salts of carboxylic acids. Additive producers do not usually disclose which metal salts are used. This has led to claims that the environment will be contaminated by heavy metals when they are released by the degrading plastics. The additive producers respond to this by saying that the metals are not “heavy” metals and are present in such small quantities that they will not significantly increase the concentrations of the metal ions already present in the soil. They have supported their claims with results from trials and calculations based on expected levels of usage.

Another aspect of bio-accumulation is the plastic particles themselves. It has been suggested that the plastic particles being hydrophobic could absorb and concentrate pollutants from the environment²¹. This would also be true of any plastic particles, whether or not they were of oxo-degradable origin³⁴. Furthermore, even if such concentration of pollutants was to occur it is not clear that it would necessarily be detrimental to the environment. There is a potential, rather than a proven risk, but some may consider that the precautionary principle should be applied.

4.3.3 Toxicological Impact

The additive manufacturers indicate that oxo-degradable plastics are non-toxic because of the many food contact and migration regulations that they comply with. These claims of lack of toxicity are not generally in contention. The possibility of toxicological impact when the metal ions are released into the environment, is discussed in section 4.3.2.

4.3.4 Recycling

Additive producers and suppliers claim that oxo-degradable plastics are recyclable. Strictly speaking this is true, however, recycling does not destroy the oxo-degradable function. There is therefore a concern among plastics recyclers that if oxo-degradable plastics are included among other plastics to be recycled, the product will also be prone to degradation. This could be particularly damaging for long-life applications such as membranes used in construction, where recycled plastic is often used. The additive producers say that the oxo-degradable function can be neutralised by the addition of sufficient stabilisers. The problem for the recycler would be knowing how much stabiliser to add, given the unknowns such as proportion of oxo-degradable potential left in the material. On this basis it seems unreasonable to claim recyclability of oxo-degradable plastics in existing recycling streams.

5 Limitations

One of the major limitations that prevented very firm conclusions being drawn was the lack of hard evidence produced by systematic, well-controlled studies carried out by independent parties. This is perhaps understandable because of the long time scales involved and the consequent high cost of such studies. Some of the reports produced as evidence to support claims, of the additive manufacturers in particular, did not contain all the original data, leading to uncertainty about the robustness of the evidence. A similar lack of robustness is apparent where evidence of potential harm caused by oxo-degradable plastics has been extrapolated from studies related only tenuously to oxo-degradable plastics.

In the stakeholder study not all those contacted replied. Most of those that responded had fairly strong and polarised views and it is possible that middle-ground opinion was under represented.

Some very specific information on the composition of additives was not obtained because of the commercial sensitivity of the information. In particular, this limits the inferences that can be made about the environmental impact of the additives in generic terms. In the event of further research being carried out, more information on the range of compositions currently used would help to limit the number of materials that would need to be tested for their environmental impact.

6 Additional resources

There are no additional resources.

Annex A: Degradation Studies: Peer-Reviewed Literature

6.1 Annex A1: Chemistry of Oxidative Degradation of Polyolefins

The general scheme of polyolefin degradation, according to Scott^{9,39,40,41,42} and others⁴³ is shown as follows:

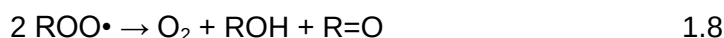
1. Initiation: polymer chains are sheared by heat, atmospheric oxygen or mechanical stress to give hydroperoxide [ROH(H₂O)] groups by various reactions.



2. Propagation:

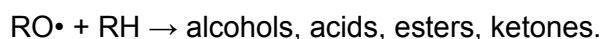


3. Termination:



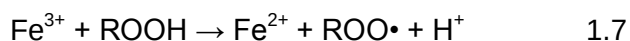
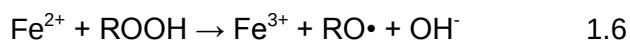
Where RH = polyolefin molecule

It is claimed that the species RO $\cdot$ can then lead to production of biodegradable intermediates:



The function of the metal ion soaps (e.g. cobalt stearate) is to catalyse the decomposition of the hydroperoxide groups. The transition metals do not catalyse the initial cleavage of the polymer chain.

Iron for example catalyses the decomposition by two processes:



The above is an example of a redox couple (a transition metal in two oxidation states).

The so-called Scott-Gilead formulation is based on variations of the following composition^{7, 8}:

- An activating complex consisting of iron or cobalt complexed with acetylacetone. This acts as an initiator of photodegradation and thermal degradation.
- A thermal stabilising complex consisting of zinc or nickel or cobalt complexed with one of the following: dialkyldithiocarbamate; dialkyldithiophosphate; alkylxanthate; mercaptobenzothiazole.

Other reactions are possible which lead to larger molecules instead⁴⁴:

Cross linking (a form of termination): $R\cdot + R\cdot \rightarrow R-R$

Intra-molecular hydrogen transfer: $-CH_2-CH_2-CH\cdot-CH_2- \rightarrow -CH_2-CH\cdot-CH_2-CH_2-$

Inter-molecular hydrogen transfer: $R'\cdot + R'' \rightarrow R' + R''\cdot$

Abstraction of hydrogen: $-CH_2-CH_2-CH_2-CH_2- + H\cdot \rightarrow -CH_2-CH\cdot-CH_2-CH_2- + H_2$

6.2 Annex A2: Evidence for Biodegradability

6.2.1 A2.1: Laboratory Degradation Studies Based on Measurement of CO₂ Evolution (Respirometric studies)

Arnaud et. al.⁴⁵ examined commercial photodegradable polyethylenes with respect to rate and extent of oxidation as measured by carbonyl formation, molar mass reduction and ability to support microbial growth.

- These tests were performed on agar, not soil

There is no reference to either O₂ uptake or CO₂ evolution: this was not therefore robust evidence for biodegradation.

In a study by Orhan and Buyukgungor⁴⁶, soil samples inoculated with *P. chrysosporium* were mixed with low-density polyethylene(LDPE)/starch blend films and biological changes of the films and soil were monitored for 6 months. The biodegradation of polyethylene starch blend film were determined by following changes in the physical, chemical and biological properties of the samples such as pH, biomass, CO₂ formation, percentage elongation (which decreases with increasing degradation), relative viscosity (which decreases with increasing degradation) and Fourier Transform Infrared spectrum (FTIR), which can reveal chemical changes in the material related to degradation.

- The test material contained 12% starch which could easily have accounted for the observed increase in CO₂ production.
- The test material did not undergo the thermal or photo activation that is claimed necessary for these materials, which is further evidence that the evolved CO₂ was from the starch.

This was not therefore robust evidence for biodegradation.

Chiellini & Corti¹⁹ used a modified experimental set-up normally used to examine pesticide degradation was adopted for testing the ultimate biodegradability of natural, synthetic and semi-synthetic polymeric materials on solid substrates such as soil and mature compost. The materials tested were polycaprolactone, PVAL, EVOH and LDPE and lignin graft copolymers. Soil and compost samples were diluted with perlite to ensure optimal conditions for microbial growth. The CO₂ evolution from LDPE showed a lag phase of >150days (Figure 1). After 567days the highest extent of biodegradation was 59% (initial inoculum 22mgLDPE/g soil).

- There was a considerable lag phase before biodegradation (as shown by CO₂ evolution) began.
- The authors refer to the two levels of treatment (22 and 45 mg/g soil) as 'replicates'
- The paper control degraded from the start of the experiment.
- The paper control was 70% degraded at the end of the experiment.

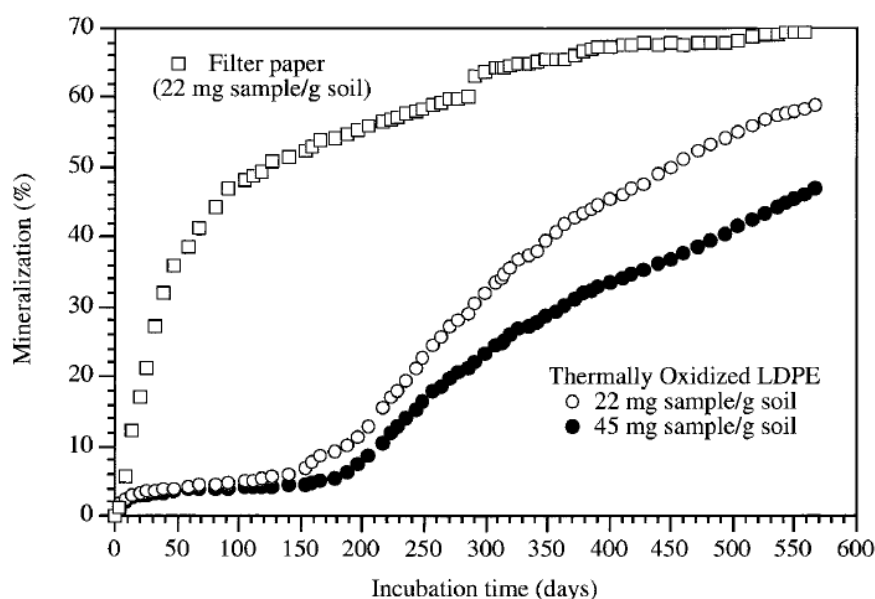


Figure 1. Biodegradation (as CO₂ evolution) of thermally oxidised LDPE in a soil burial test¹⁹

It would appear that this experiment and its results are reported more than once in the literature elsewhere by the same authors¹⁴. There is therefore some duplication of evidence in the literature and merely counting the number of references from an author would not necessarily give the most accurate record of the weight of evidence for biodegradation.

In a later report in 2007 Chiellini et. al.⁴⁷ report 60-70% conversion of oxo-degradable polyethylene to CO₂ after 800 days soil burial following thermal treatment (55°C is inferred from cited prior publications by the same author)

Chiellini et. al.¹⁶ reported 40-50% biodegradation of thermally oxidised (accelerated ageing at either 55°C or 70°C according to the author but not specified) oxo-degradable polyethylene films in river water. The curves are reproduced in Figure 2 and Figure 3. The shapes of the curves imply that the conversion to CO₂ was reaching a maximum extent at around 50%. However the highest degree of degradation is for extracts of the oxidised polymer which would have a lower molecular weight. It should be noted that the biodegradation for the entire film in either figure was not more than 8%.

Although the study is well-presented, it is not robust evidence for biodegradability of the total material.

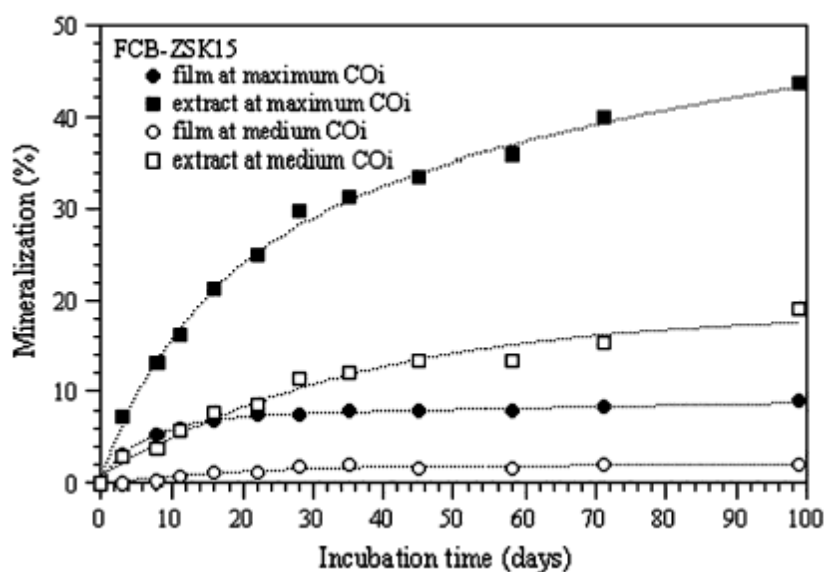


Figure 2. Biodegradation profiles of thermally treated FCB-ZSK15 films and acetone extracts in river water medium at room temperature.

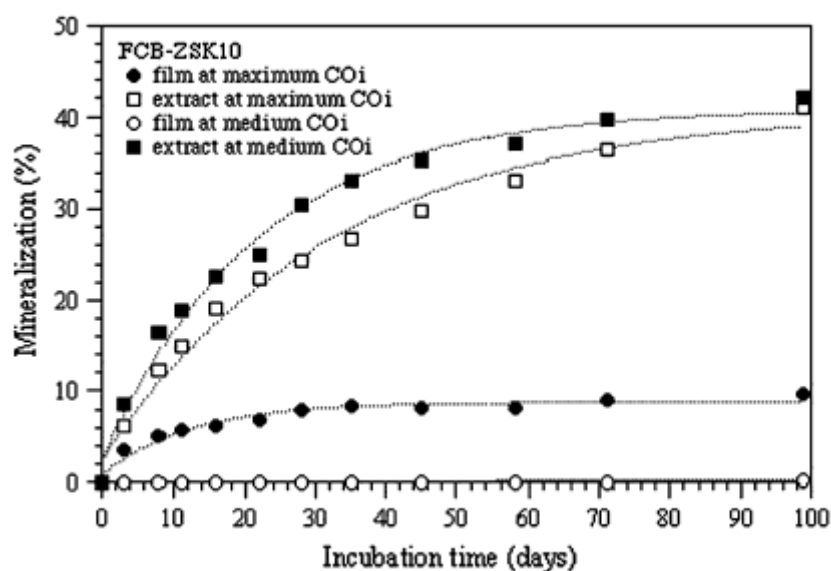


Figure 3. Biodegradation profiles of thermally treated FCB-ZSK10 films and acetone extracts in river water medium at room temperature.

The most rigorous test on the biodegradability of oxo-degradable plastics (as found in this review) was conducted by Feuilloy et. al.¹⁷. Three materials were tested, details of which are given in Table 1. All materials were subjected to ten tests including EN and ASTM standard tests as detailed in Table 2. The results were as follows:

- Oxo-degradable polyethylene showed a biodegradation of <15% as measured by the respirometric test. This is clearly shown in Figure 4
- The paper positive control showed a biodegradation of >90%.
- The biodegradation of Mater-Bi was 75-88% in all tests
- The biodegradation of Ecoflex was 5-95% in all tests
- The biodegradation of oxo-degradable polyethylene ranged from negative values in some tests to 1.8% in nine of the tests
- The “biodegradation” of oxo-degradable polyethylene as measured by the soil burial test was 90%. However, this assessment is based on visual assessment rather than actual measurement of CO₂ released, that is to say, the test showed that 90% was not visible to the naked eye after 11 months.

This is a highly robust study that shows the limited degree of biodegradation by standard test procedures.

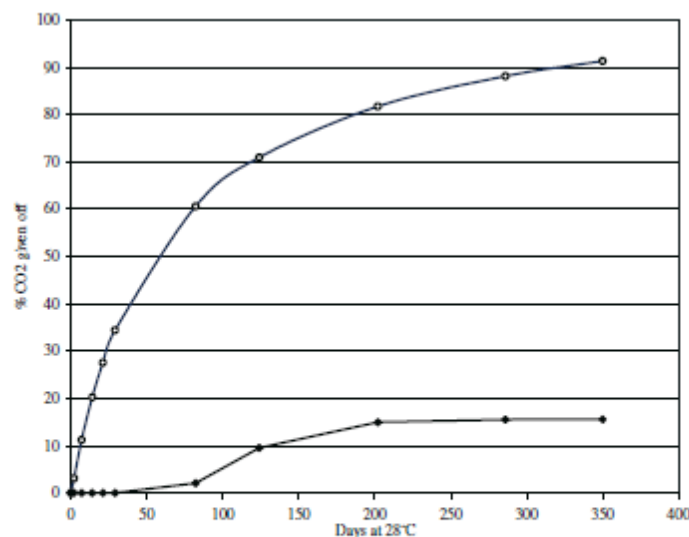


Fig. 1. Respirometric test on real soil (ASTM D5988-96 modified). The percentage of CO₂ released as a function of time for the reference paper and PE with additives. °, represents reference paper; and ♦, represents material C (PE with peroxidant).

Figure 4. Respirometric test on biodegradation of PE with prooxidant additives compared to a paper control. The results show that the biodegradation of the PE sample was 15%. (Figure taken from Feuilloy et al ¹⁷).

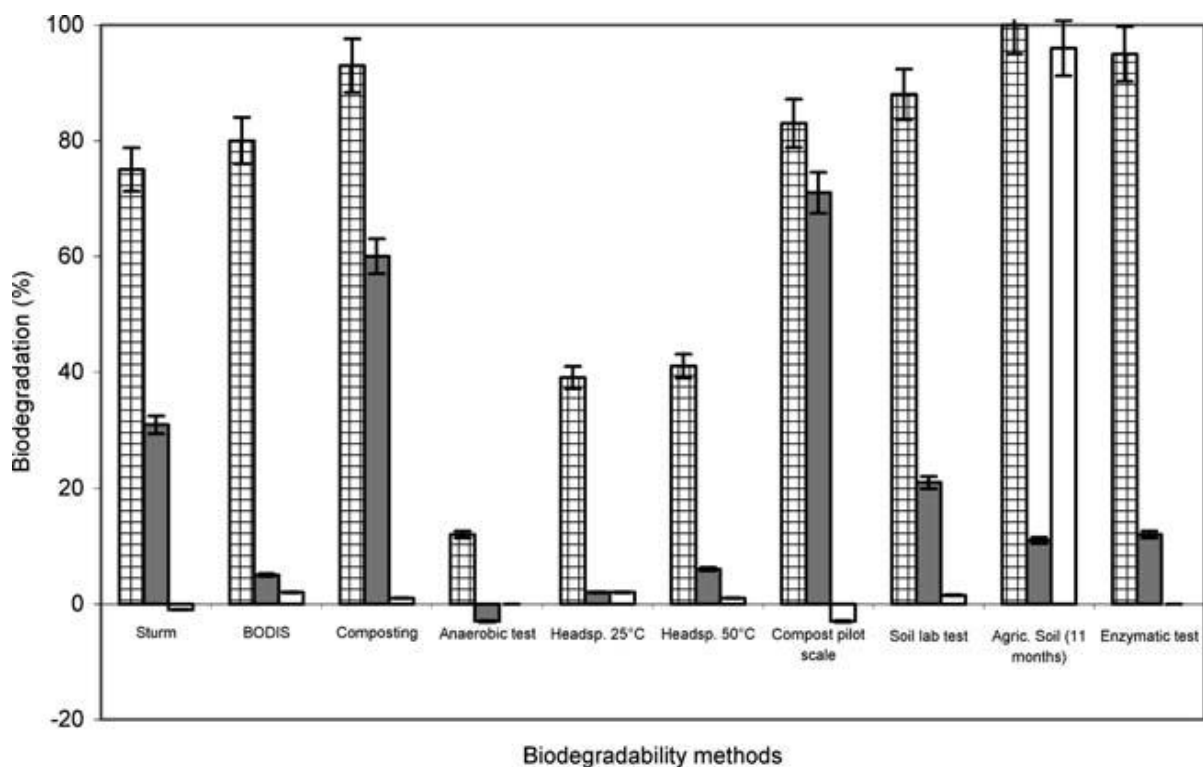


Figure 5. Comparison of the percentage biodegradation of materials A, B and C (see Table 1) according to the tests given in Table 2. The tests are shown left to right in the same vertical order in Table 2.

Table 1. Description of three packaging materials tested for biodegradation (from Feuilleley et al ¹⁷).

Material	Description	Thickness (micron)
A: Mater-Bi (Novamont)	PCL/Starch (60:40w/w)	50
B: Ecoflex	Aliphatic/aromatic polyester	60
C: Actimaïs (SMS Trioplast)	PE+pro-oxidant additive	36

Table 2. Tests used to evaluate biodegradation of the materials in Table 1(from Feuilleley et al ¹⁷).

Test Name	Details
Sturm	Sturm test (OCDE 301B, ISO 14852) for 180 days
Bodis	Test on the oxygen demand in solid medium (ISO 14851) for 117 days
Compost	Compost test under laboratory conditions (ISO/DIS 20200, EN 261085, ISO 14855) for 50 days
Anaerobic	Anaerobic tests (ASTM D5210) for 58 days*
Headsp 25°C	Closed bottle at 25°C (OCDE 301D, ASTM D5988-96 modified) for 48 days
Headsp 50°C	Closed bottle at 50°C (OCDE 301D, ASTM D5988-96 modified) for 48 days
Compost pilot scale	Pilot compost test (EN 14045) for 84 days
Soil test (lab)	Test on reconstructed soil in the laboratory (DIN 53739) for 84 days
Agricultural soil test	Buried sample test in real agricultural soil for 330 days
Enzyme test	Enzyme test

*In the original article, the authors cite EN13432 although no anaerobic test is specified in that standard.

In 2003 Jakubowicz¹⁸ reported the biodegradation of two samples of oxo-degradable polyethylene both containing manganese stearate as oxidation initiator, with the concentration in one sample being twice that of the other.

The materials were thermally treated at 70°C in air for 4 weeks to produce oxidation products by thermo-oxidative degradation of the polyethylene. The samples were then incubated in soil at 60°C and the biodegradation was followed by measuring the CO₂ released. After 200 days of incubation the biodegradation of the sample containing the lower amount of oxidant was 60.3% and that of the larger amount was 65.1%. The author noted that the shape of the curves indicated that biodegradation was still proceeding at this point.

From the data given in the paper, the thermal treatment would have reduced the molecular weight of the samples to 5000 or less, at which point the author maintains that the material becomes biodegradable.

The author also concluded, from Arrhenius plots of the data, that for an in-use temperature of 25°C the time taken to reach a molecular weight of 10000 (i.e. twice that of the 5000 required for biodegradability) would be between 2.5 and 4.5 years depending on the manganese stearate content.

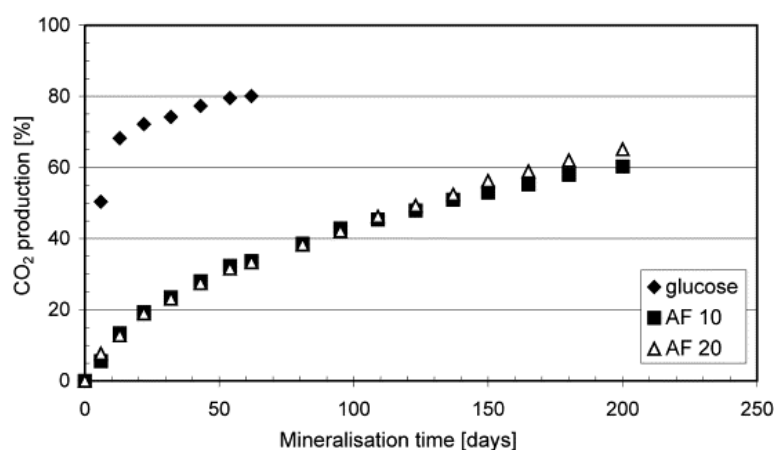


Figure 6. Biodegradation of thermally aged (70°C, 4 weeks) oxo-degradable polyethylene in soil¹⁸

6.2.1.1 A.2.1.1: Studies Involving Specific Microbial Challenge

Koutny et. al.¹¹ subjected high density polyethylene film (HDPE) and low density polyethylene film (LDPE) both containing antioxidants and pro-oxidants to an abiotic pre-treatment consisting of photooxidation and thermo-oxidation corresponding to about 3 years of outdoor weathering. The samples were then inoculated with defined microbial strains particularly with *Rhodococcus rhodochrous* and *Nocardia asteroides*, incubated up to 200 days and during the period their metabolic activities were followed by measuring adenosine triphosphate content. Simultaneously the cultures were also monitored by optical microscopy and FTIR spectroscopy. The first initial phase of fast growth caused by the presence of low molecular extractable compounds was followed by a long period of stabilised metabolic activity suggesting that microorganisms continued to gain energy from the substrate but evidently at a much slower rate. Complementary analysis performed at the end of incubation

revealed that during the experiment time biodegradation processes probably affected surface layer of materials only.

Conclusions

The study showed the growth of micro-organisms on the polymer surface.

There were no respirometric tests.

The abiotic pre-treatment time was equivalent to 3 years of outdoor weathering.

6.2.2 A2.2: Proof of the Breakdown Mechanism

The claim is made that the additives cause the breakdown of the polyethylene chains by a free-radical mechanism, with the free radicals being initiated by heat and UV light. The breakdown mechanism as given above predicts that certain compounds such as carboxylic acids, also known as fatty acids, will be formed in the process. The mechanism also results in the formation of a chemical structure, known as a *carbonyl* group, which is easily detected in materials by the technique known as *Fourier Transform Infrared Spectroscopy* (FTIR). The carbonyl index is a measure of the concentration of carbonyl groups in a material and should increase as a substance is oxidised. The free radicals (e.g. R•) produced can be detected by a technique known as electron spin resonance.

Albertsson et. al.²⁶ demonstrated the increase in carbonyl index with UV irradiation and confirmed the existence of free radicals in the UV-treated oxo-degradable polyethylene using electron spin resonance. No information about the intensity of the irradiation is given other than that 300W lamps were used, therefore it is difficult to say how the treatment related to a real-world situation.

If a carbon-containing material such as polyethylene is made in which some of the carbon is in the radioactive form known as carbon-14 (¹⁴C), then carbon dioxide (CO₂) released by breakdown of that material will also contain ¹⁴C. Such substances are known as radio labelled materials. Thus in a composting or biodegradation test using a radio labelled material, the radio labelled carbon dioxide can only have come from that material and therefore the extent of biodegradation can be accurately measured. It is however vital to know exactly what is the ¹⁴C content of the test material.

Karlsson et. al.²⁷ measured the ¹⁴CO₂ release from irradiated PE containing a photoinitiator (palmitate iron carboxylate-Fe(III) hydroxide). After UV irradiation the samples were mixed with humid soil and the CO₂ released was captured and determined. Increasing the amount of oxo-degradable polyethylene increased the CO₂ evolution. The extent of biodegradation of the PE could not be calculated from the data as the original ¹⁴CO₂ content of the PE was not given. This was not therefore a robust quantitative measurement of the biodegradation of polyethylene.

In other studies⁴⁸⁴⁹ workers have identified over 60 degradation products from a oxo-degradable polyethylene-starch which had been degraded at 95°C in water for 30 weeks. The majority products were dicarboxylic acids, monocarboxylic acids and n-alkanes; the minority products were lactones, aldehydes and alcohols.

It should be noted that the degradation conditions were extreme (30 weeks in water at 95°C) and do not relate to any current waste treatment processes.

Cornell et. al.⁵⁰ conducted rigorous tests on the effect of intensity and type of UV irradiation on PE, PP and oxo-degradable polyethylene. They concluded that while the oligomer fractions supported microbial growth, the high polymers gave minimal or no growth. It was concluded that photo oxidative degradation of polyolefins did not per se induce progressive attack by microorganisms. However oligomers generated by photooxidation augment those already present in the polymer.

Oldak et. al.²⁸ studied the effect of UV irradiation on PE, cellulose and PE-cellulose films. They concluded that the pure PE and cellulose fibres were resistant to UV irradiation. Blends of the two components were susceptible to photo- and biodegradation: the susceptibility depended on the composition.

The evidence for the mechanism of breakdown is highly robust.

The evidence also indicates that biodegradation is possible, but does not prove that biodegradation is either complete, nor does it necessarily show that the biodegradation is rapid.

Overall conclusions

Many reports include the terms 'biodegradability' or 'biodegradation' in the title or text. However, some studies^{26, 27} use the terms to refer to evidence of microbial growth on the surface of the polymer whereas other studies use the term to indicate that the PE samples were subjected to a biotic environment (soil, compost) as part of the experimental procedure²⁸.

Only one of the studies cited in this section refer to true biodegradation experiments where the release of CO₂ from PE-amended soil is compared with that of a positive control comprising cellulose in soil.

6.2.3 A2.3: Environmental Degradation studies

We have so far found three references to environmental testing of oxo-degradable polyethylene. 'Environmental testing' in this context refers to tests where the putative degradable material was tested in outdoor conditions rather than in simulated controlled conditions in a laboratory. Inevitably, such testing is less controlled and subject to the climatic conditions prevailing at the time. However, such tests provide useful information on how the material will behave in real-life conditions.

In 1993 Breslin⁵¹ reported the rate and extent of deterioration of starch-plastic composites over a 2-year period for samples buried in a municipal solid waste landfill. The deterioration of the starch-plastic composites following exposure was determined by measuring changes in tensile properties, weight loss, and starch content of samples retrieved from the landfill. Starch loss of 25% for linear low-density polyethylene and 33% for low-density polyethylene starch-plastic composite films was measured following 2 years of landfill burial. Starch-plastic composites did not fragment or lose mass during the 2-year landfill burial. The limited degradation observed for the starch-plastic composites was attributed to the ineffectiveness of the prooxidant additive to catalyze the thermal oxidation of the polyethylene or polypropylene component of the starch-plastic composite under the environmental conditions present within the landfill.

In a study on photo-biodegradable PE mulching films in China⁵², oxo-degradable polyethylene were made from four “photo-biodegradable” (PBD) masterbatches (Starch + unknown photo activator composition). These were used as seed mulches from mid-April to early September.

The films were evaluated by recording the induction period (time taken for cracks 1-2cm in length to appear). This was between 46 and 64 days (Table 3).

Table 3. Time taken for fragmentation stages to appear for four oxo-degradable PE samples.

Stage	I	II	III	IV	V
Description	1-2cm slits appear	2-20cm slits appear	20-50cm slits appear	Film breaks up	Very little film on soil surface
Film Sample	Time to reach stage from April 25 (days)				
A	41	45	47	56	72
B		41	43	48	77
C		46	51	70	99
D		48	56	75	94

Although the authors state that four films were assessed in a soil burial test, only the results for one film were presented.

Table 4. Weight loss over 32 days soil burial of an oxo-degradable PE sample.

Time after burial (days)	10	19	32
Weight Loss (%) (based on 1 measurement)	9	13	19

The study did not prove biodegradability. Assessment of the degradation is qualitative and of limited value. This is not therefore very robust evidence.

Davis et. al.³⁵ evaluated degradable PE sacks used for kerbside collection of biodegradable municipal waste (BMW) in windrow composting. The bags and contents were shredded and added to windrows. The composting period was not less than 12 weeks and the windrows were turned fortnightly. Four windrows contained degradable bag residues and four control windrows contained no compostable bags.

Table 5. Analysis of compost material in control windrows and windrows containing degradable PE refuse bags.

Designation	Sample Wt, kg	Reject Wt, kg	% rejects to compost	% rejects that are PE
Windrow 1 Control	41.4	7.9	19.3	
Windrow 1 PE Bag	42.8	11.3	26.5	0.42
Windrow 2 Control	36.4	3.6	9.9	
Windrow 2 PE Bag	37.6	8.8	23.4	0.31
Windrow 3 Control	41.6	3.2	7.7	
Windrow 3 PE Bag	31.6	5.4	17.1	0.39
Windrow 4 Control	45.0	7.9	17.5	
Windrow 4 PE Bag	34.7	8.1	23.3	0.34

The authors report that the percentage of rejects in the windrows containing PE bags was higher than the control in all four replicates.

The report also notes that the time-averaged temperature of each PE windrow was lower than its control. The PE windrows were also wetter and more difficult to turn. No explanation was given. The C:N ratio of the PE windrow compost was higher than the control; a higher C:N ratio is less desirable. The authors suggest this was caused by slower anaerobic decomposition caused by confinement within the PE shreds.

The authors used a paired treatment-control experimental design and rigorous statistical analysis; confidence in this data is therefore high.

In 2003 Bonhomme et. al.³⁰ studied the spectral changes in oxo-degradable polyethylene samples following heating. The induction period (induction of increase in the 1715cm⁻¹ carbonyl signal) was between 300 and 400 days for samples heated at 40°C.

6.2.4 A2.4: Evidence for Cross-Linking of Photodegradable PE

Feuilloley et. al.¹⁷ retrieved PE fragments from a soil that had a PE mulch applied 2 years previously. Fragments of 5-70um size were recovered but not quantified other than to be described as 'numerous'. The low solubility in hot xylene was strong evidence that the PE in these fragments was cross-linked, possibly as a result of the free-radical mechanism involved in the degradation. The authors stated in the discussion: 'Therefore that large PE fragments in this state cannot be bio assimilated by soil bacteria, neither further photo-degradation, nor large cumulative effects in soil cannot be, therefore, ruled out'.

Rapra report CTR47562⁵³ contains data on the gel content of oxo-degradable polyethylene samples that had been thermally aged at temperatures between 40°C and 70°C. The

results are given in Table 6. All the values are below the 5% criterion set by ASTM D6954 (note 6).

Table 6. Percentage of soluble and insoluble material remaining after thermal ageing treatments.

Sample	% Soluble	% Gel
Unaged	97.4	2.3
9 days @ 70°C	98.8	1.2
14 days @ 60°C	98.6	1.4
39 days @ 50°C	99.0	1.0
90 days @ 40°C	98.8	1.2

Conclusions

- There is field evidence that persistent plastic fragments can remain after application of a degradable mulch film. However laboratory investigation suggests that the extent of cross linking under laboratory conditions is small.
- There is insufficient peer-reviewed evidence to make a definite conclusion.
- Further quantifiable field investigations are required on this subject.

6.3 Annex A3: Evidence for Bioaccumulation

6.3.1 A3.1: Evidence of Accumulation of Pro-oxidant Metals in Plants

Wolfe et. al.³¹ conducted a study in which lettuce and green peppers were grown in the greenhouse and field in soil into which was incorporated photodegraded plastic at rates equivalent of up to 30 years of repetitive annual plastic use. Dithiocarbamate residues were not detectable in the harvested crop or soil samples. Residues of nickel showed no consistent differences between treated or control crop and soil samples.

6.3.2 A3.2: Evidence for Accumulation of oxo-degradable polyethylene residues in organisms

The investigation did not find any published evidence specifically concerning the accumulation of oxo-degradable polyethylene residues in any organisms. However, it has been shown that microscopic plastic fragments ingested by the marine mussel *Mytilus edulis*, end up in the circulatory system and therefore must have penetrated the gut wall⁵⁴. It was also noted that they persisted there for 48 days after ingestion. There were no significant biological effects reported from this short-term exposure.

6.4 Annex A4: Environmental Impact

6.4.1 A4.1: Evidence for Plant Toxicity

There are very few references to toxicological studies on photo- or oxo-degradable polyolefins or their residues.

Davis et. al.³⁵ tested germination levels of tomato seeds (*var. Money Maker*) in compost from windrows containing Biodegradable Municipal Waste (BMW) which had been collected from the kerbside in degradable polyethylene sacks (labelled as 'compostable' by the manufacturers, provenance unknown). A control compost was prepared from BMW without degradable bags present. A peat control was also run. The conclusions were that there was no visible sign of compost toxicity in any of the samples. The bioassay also indicated that the presence of the shredded degradable PE and its degradation products did not inhibit plant growth nor seed germination. The authors pointed out that a bioassay cannot predict the long-term cumulative effect of repeated applications of degradable PE.

Table 7. Plant germination in compost from control windrows and windrows containing degradable PE bags state author

Analysis	Control Windrow	Windrow + Degradable PE
No. weeds/litre	0	0
Dilution ratio compost:peat ¹	1:2	1:1.3
Germination ²		
14 days	95%	95%
28 days	95%	100%
Vigour Score ³		
14 days	4.5	4.25
28 days	3.75	3.75
Phytotoxicity Score ⁴	0	0
Total fresh weight per plant ⁵	51%	50%

¹Dilution with fresh peat to adjust water soluble N to 240mg/l
²Germination as % of germination in peat –based control
³Vigour score on scale 1-5
⁴Phytotoxicity 0 = no visible toxicity 10 = death
⁵Total fresh weight of seedlings as % of total fresh weight of seedlings grown in peat control

Conclusions

- There are limited peer-reviewed studies on the phytotoxic effects of compost following application of oxo-degradable polyethylene material.
- The evidence available is robust
- The evidence so far suggests that there is little or no phytotoxic effect.
- There is no peer-reviewed evidence of the long-term effect of repeated application of degradable PE.

6.4.2 A4.2: Evidence of Environmental Toxicity

Although Bonora & Corte⁵⁵ claim that composted PE containing Ciba's ENVIROCARE™ additives do not show any toxicity to the organisms according to tests listed in Table 8, no data are presented. This paper is more of a promotional brochure than an academic paper.

Table 8. Biotoxicity assays conducted by Bonora et. al. (2003)

Organisms	Test
Daphnia magna	Immobilization test according to ISO 6341
Earthworm	Acute toxicity test according to ISO 11268-1
Cress	ISTA
Oat and Lentil	ISO 11269-2

6.4.3 A4.3: Environmental Effects – Residues

A study conducted by Wolfe³⁰ did not find any evidence for nickel accumulation in soil after the application of the equivalent of 30 years of continuous annual application of oxo-degradable polyethylene mulch containing nickel dithiocarbamate.

6.4.4 A4.4: Evidence for Plastic Fragments as Accumulators of Toxins

The investigation has found no record of any tests on whether plastic fragments resulting from the physical breakdown of plastic items in the environment accumulate and concentrate toxic substances found in the terrestrial environment. However, there have been studies carried out on resin pellets, which are a current source of concern about marine environmental pollution³³. Resin pellets are the main form in which newly-manufactured plastics (polymers) are transported from the place of production to factories where they are converted to products for sale. The main means of international transportation is by sea and significant quantities may be lost as a result variously of shipping accidents or cargo mishandling^{22, 56}.

Mato et. al.³⁴ found that PCBs, DDE, and nonylphenols (NP) were detected in polypropylene (PP) resin pellets collected from four Japanese coasts. Concentrations of PCBs (4-117 ng/g), DDE (0.16-3.1 ng/g), and NP (0.13-16 µg/g) varied among the sampling sites. These concentrations were comparable to those for suspended particles and bottom sediments collected from the same area as the pellets. Field adsorption experiments using PP virgin pellets demonstrated significant and steady increase in PCBs and DDE concentrations throughout the six-day experiment, indicating that the source of PCBs and DDE is ambient seawater and that adsorption to pellet surfaces is the mechanism of enrichment. The major source of NP in the marine PP resin pellets was thought to be plastic additives and/or their degradation products. Comparison of PCBs and DDE concentrations in marine PP resin pellets with those in seawater suggests their high degree of accumulation (apparent adsorption coefficient: x100,000 - x1,000,000). The high accumulation potential of these compounds suggests that plastic resin pellets serve as both a transport medium and a potential source of toxic chemicals in the marine environment.

Such is the scale of this process that an initiative, "International Pellet Watch", is using data from pellet analysis to monitor persistent organic pollutants (POP) on a global scale⁵⁷.

In 2003 and 2004 Rios et al.⁵⁸ collected and analysed pre-production thermoplastic resin pellets and post-consumer plastic fragments for evidence of contamination by persistent organic pollutants. Samples were taken from the North Pacific Gyre (a region that has been accumulating marine plastic debris for several decades), and selected sites in California, Hawaii, and from Guadalupe Island, Mexico. The total concentration of PCBs ranged from 27 to 980ng/g; DDTs from 22 to 7100ng/g and PAHs from 39 to 1200ng/g, and aliphatic hydrocarbons from 1.1 to 8600 µg/g. They developed analytical methods to extract, concentrate and identify POPs that may have accumulated on plastic fragments and plastic

pellets. They concluded from the results of this study that plastic debris can act as a trap for persistent organic pollutants.

In 2007 Teuten et al.³² examined the uptake and subsequent release of phenanthrene (a PAH) by three plastics: polyethylene, polypropylene and polyvinyl chloride (PVC). The accumulation of phenanthrene from seawater onto the plastics varied by more than an order of magnitude (polyethylene > polypropylene > polyvinyl chloride (PVC)). In all cases, sorption to plastics greatly exceeded sorption to two natural sediments. They also found that desorption occurred more rapidly from the sediments than from the plastics. The effects of adding very small quantities of plastic with sorbed phenanthrene to sediment inhabited by the lugworm (*Arenicola marina*) were also evaluated. The authors estimated that adding as little as 1 mg of contaminated polyethylene to a gram of sediment would give a significant increase in phenanthrene accumulation by *A. marina* and that plastic fragments may be important agents in the transport of hydrophobic contaminants to sediment-dwelling organisms.

Feuilloley et. al.¹⁷ recovered PE fragments from a soil two years after covering with a PE mulch film. The size fraction was 5-70µm. Tests with hot xylene showed strong evidence of cross-linking. Cross linking is a chemical reaction that can occur in polymers when free radicals are generated by the same processes that are described in Annex A1. It is a process by which short polymer chains can be joined up to make longer chains and also in which linear chains can become branched as a result of being joined within the chain rather than at the ends. The significance of the result of this test is that it indicates that polyethylene was recoverable from a field two years after application of a mulch film that was described as degradable and also that the fragments recovered appeared to have undergone a process that would have rendered them more stable rather than less.

Davis et. al.³⁵ analysed Cu and Co in compost from windrows containing oxo(?)degradable PE bags. They concluded that the data did not indicate that the constituent metals within the PE sacks contributed to the increase in the metals detected within the final compost matrix. This is borne out by the data for Co although the Cu data seems to suggest an increase (Table 9). The authors did not present the standard error of the data points.

Table 9. Properties of compost from control windrows and windrows containing degradable PE bags.

Determinand	Control		With oxo-degradable polyethylene		Units
	Start	Finish	Start	Finish	
Dry matter	49.3	58.5	46.8	55.3	%
C:N Ratio	13.1	11.1	18.1	12.1	Ratio
Total Copper	32.2	57.0	36.9	173.4	mg/kg
Total Cobalt	4.7	3.8	5.0	4.9	mg/kg

Conclusions

- There is evidence that PP pellets can act as accumulators of hydrophobic molecules in the marine environment.
- There is insufficient peer-reviewed data to form a definite opinion on the toxicology of pro-oxidant additives

6.5 Annex A5: Evidence for Toxicological Effect of Oxo-degradable Polyolefins

6.5.1 A5.1: Food Migration Tests

RAPRA Confidential Technical Report 46137 (freely available online) describes food contact tests conducted according to European Directive 2002/72/EC relating to plastics materials and articles intended to come into contact with foodstuffs and its amendments to date (2004/1/EC, 2004/19/EC and 2005/79/EC). The article appears to describe the migration of two additives present in the masterbatch into 3% Acetic acid; 10% ethanol and olive oil. The additives are not identified. The report concludes that the migration of the additives in each case was below the Directive limit of 10mg/dm³.

Strandberg & Albertsson⁵⁹ presented results showing a correlation between the carbonyl index of oxidised polyethylene and propionic acid content. Butanoic and hexanoic acids in the oxidised PE were also found to correlate well with reported off-flavours in water extracts of oxidised PE.

6.6 Annex A6: Life Cycle Assessment (LCA)

To date, there are three full LCAs carried out that include oxo-degradable polyethylene bags and compare them to other polymers including PLA and non-degradable PE. One study was carried out in 2003 for the Australian Department of the Environment and Heritage⁵ while a later study in 2008 was carried out for the National Non-Food Crops Centre in the UK⁶. The most recent assessment was published in Australia in 2009⁶⁰.

In the 2003 Australian assessment, the functional unit was defined as, “a household carrying approximately 70 grocery items home from a supermarket each week for 52 weeks” thus representing 3640 items. Some results of this assessment are shown in Figure 7 to Figure 9, which represent the impact of twelve different bag materials on greenhouse gas production, abiotic depletion (depletion of mineral reserves such as crude oil) and eutrophication (input of excess nutrients into freshwater, leading to algal bloom and possible death of freshwater animals). In all three figures, the higher the bar, the greater the negative impact of the material on that particular parameter. It can be seen that in each case the impact of oxo-degradable polyethylene is similar to non-degradable PE. Of all the materials, Kraft paper consistently had the greatest impact. After Kraft paper, the only parameter in which HDPE or oxo-degradable bags had an impact significantly greater than the other materials was abiotic depletion. In the case of greenhouse gas emissions, the impact of oxo-degradable PE was considerably less than poly(lactic acid) but similar to those of all the other materials. The impact of oxo-degradable polyethylene bags on eutrophication was less than that of the biopolymer bags.

The more recent assessment⁶⁰ produced in Australia concluded that oxo-degradable bags conveyed no advantage in landfill compared to conventional polyethylene bags and also concluded that there was a negative impact on recycling due to uncertainty about their effect on recycled plastic.

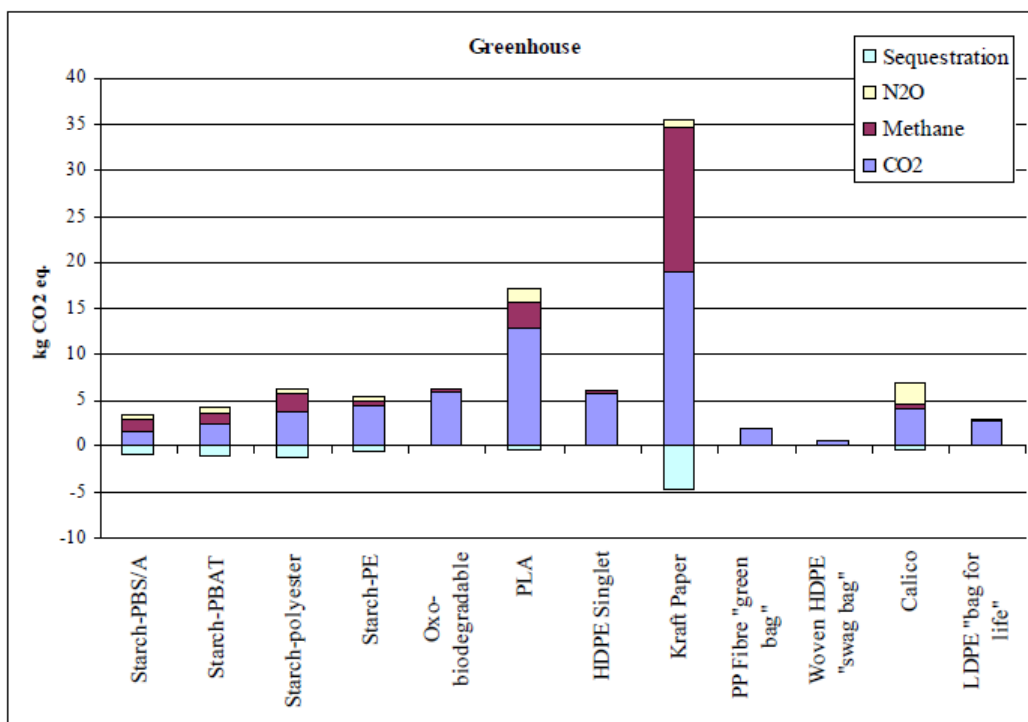


Figure 7. Greenhouse gas emissions for a range of carrier bag materials⁵.

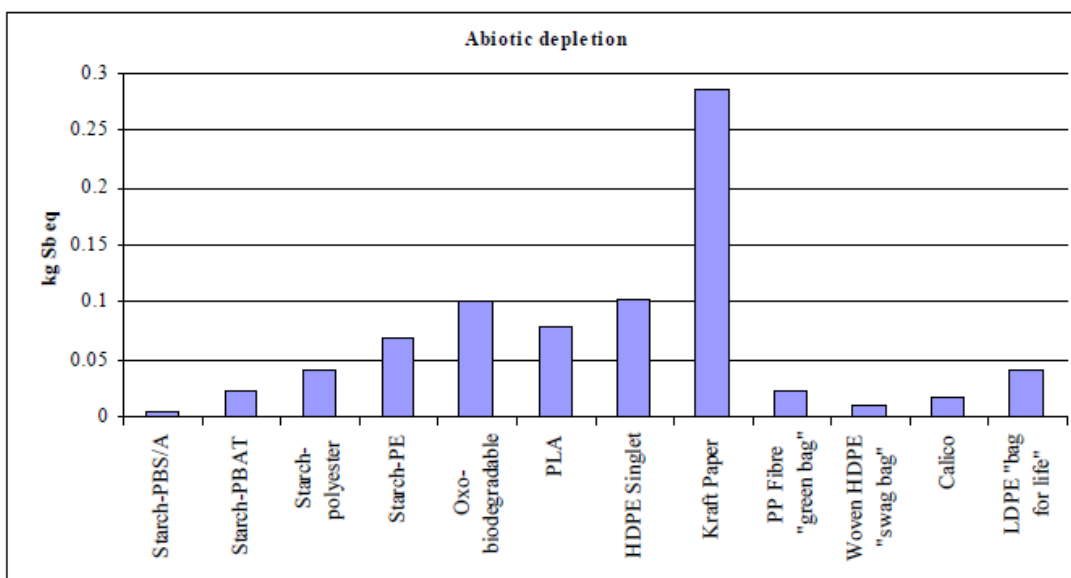


Figure 8. Resource depletion for a range of carrier bag materials⁵.

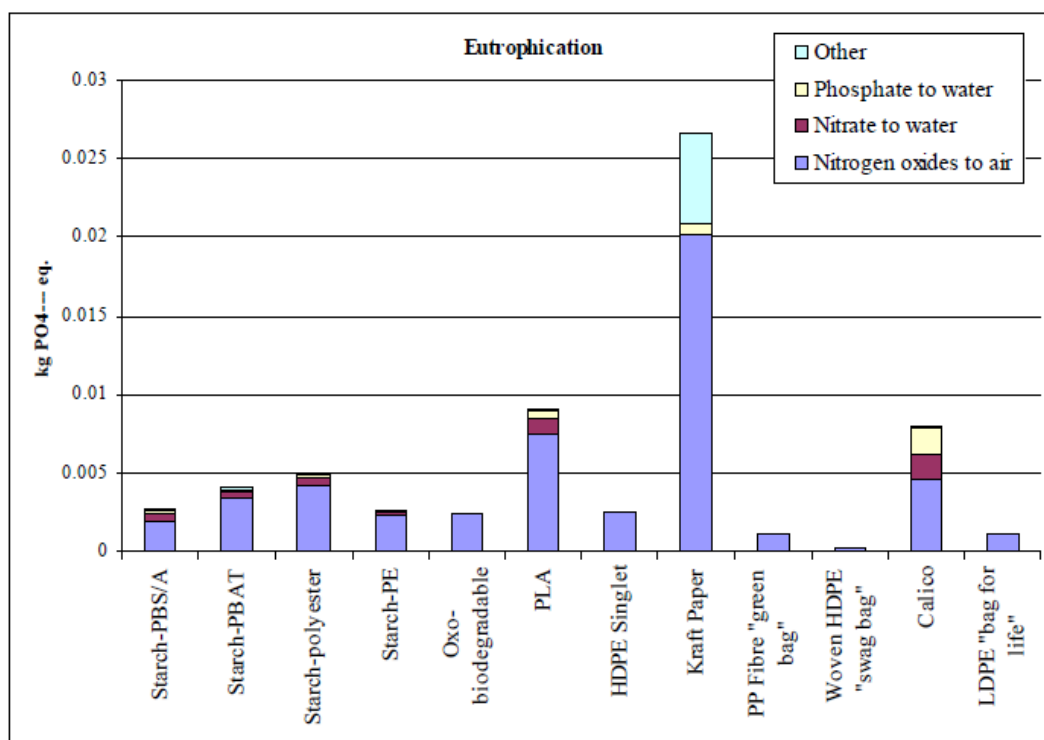


Figure 9. Eutrophication potential for a range of carrier bag materials⁵.

The functional unit for the UK LCA⁶ was defined as “the carrying of 10,000 litres of grocery items from the supermarket to the home in carrier bags filled to 75% of the nominal bag volume”. The four options considered included HDPE bags with recycling (thereby giving 90% avoided production), Mater-Bi bags (made from plant material) and oxo-degradable bags disposed of either by landfill or incineration. The LCA found that recycling HDPE had the lowest environmental impact of all the options considered and that this was considerably lower than disposing of oxo-degradable bags either by incineration or by landfill. The impact of the (biopolymer) Mater-Bi bags was less than that of the oxo-degradable bags irrespective of the disposal method (composting, landfill, incineration with energy recovery). This LCA also included the assembly and distribution of the bags where it was found that the greatest impact of the oxo-degradable bags was on depletion of reserves such as oil, coal and gas.

6.7 Annex A7: Conclusions

- Full biodegradability has not been shown for oxo-degradable polyethylene in any of the tests reported to date.
- Most claims of biodegradability are based on extrapolations of laboratory tests
- There is evidence for cross-linkage of oxo-degradable PE in the soil leading to persistent fragments.

Annex B: Results of the Non-Peer-Reviewed Literature Survey

6.8 Annex B1: Performance Evaluation by the University of California

In June 2007 a report entitled “Performance Evaluation of Environmentally Degradable Plastic Packaging and Disposable Food Service Ware – Final Report”²⁰ was published by the Chico Research Foundation (CRU) based at the University of California. This study was carried out for the California Integrated Waste Management Board (CIWMB) which reports to the California Environmental Protection Agency and the State Governor. All images and data in this section are from this report.

The research was guided by an advisory committee whose members are listed in Table 10. It should be noted that the committee comprised representatives from biodegradable plastic manufacturers and oxo-degradable additive manufacturers.

Table 10. Advisory committee to the University of California’s performance evaluation of degradable plastic ware.

Committee Member	Organisation
Dr Robert Dorsey	Clorox
Mr Lee Doty	Oxo Bio Organization
Mr Evan Edgar	Inc.
Mr Steve Mojo	BPI
Dr Ramani Narayan	MSU
Dr Robert Whitehouse	Metabolix Inc

The following is a summary of the salient findings of the work.

Biodegradability

Laboratory Measurement of Compostability

The University of California measured the biodegradation of several materials according to the method of ASTM D5338. The materials were incubated in mature (18 months old) compost in closed containers (Figure 13) with air flow for 45 days and the CO₂ released was assessed.

The control compost sample showed no CO₂ evolution (Figure 10) therefore any CO₂ evolved was actually due to the polymer being tested.

The cellulose positive control (Figure 11) showed 72% biodegradation conversion whereas the oxo-degradable bag (Figure 12) was very close to that of the compost control.

The results showed that all the biodegradable materials except the polythene negative control and the oxo-degradable bag showed 60% or greater conversion to CO₂ (Table 11). The conversion of the oxo-degradable bag was less than 2.19% over the 45 day test period.

Table 11. Biodegradation data for degradable plastic service ware items tested by ASTM D5338²⁰.

Material	Biodegradation Conversion %
Cellulose positive control	71.99
Kraft paper positive control	61.91
Mirel bag	64.03
PLA straws	61.22
Sugar cane plate	61.22
Corn-based BioBag trash bag	60.47
Ecoflex bag	60.14
Blank compost control	1.69
Polyethylene negative control	1.70
Oxo-degradable bag	2.19

This evidence is considered to be **highly robust** for the following reasons:

- ASTM method D5338 was followed without modification.
- A blank compost sample and a positive cellulose control were tested.
- The measurements were carried out in triplicate for each test material. However, the variability in the data is not shown and error bars would have increased the robustness of this evidence.
- The research was conducted under the guidance of a peer group of academic, industrial, and state government representatives reviewing and providing input through all steps of the study from the design of the study and validation of data to the final report.

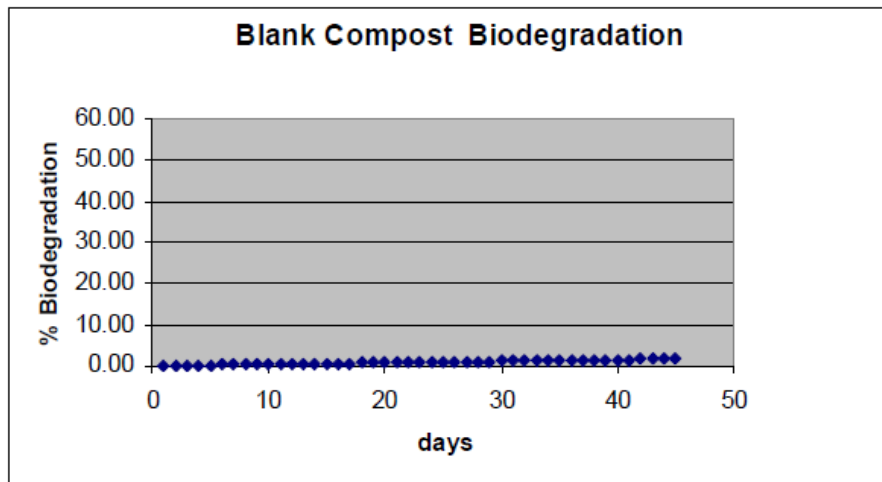


Figure 10. Blank (compost) control tested by ASTM D5338 (laboratory biodegradation test).

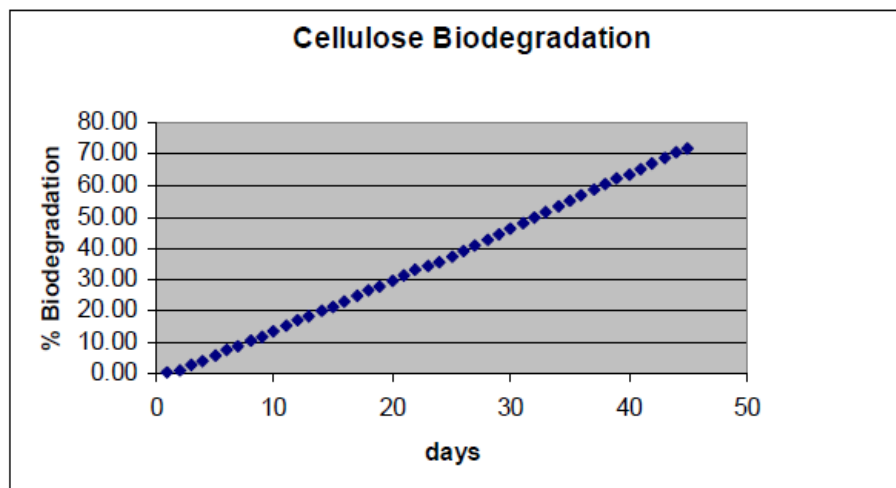


Figure 11. Cellulose control tested by ASTM D5338 (laboratory biodegradation test).

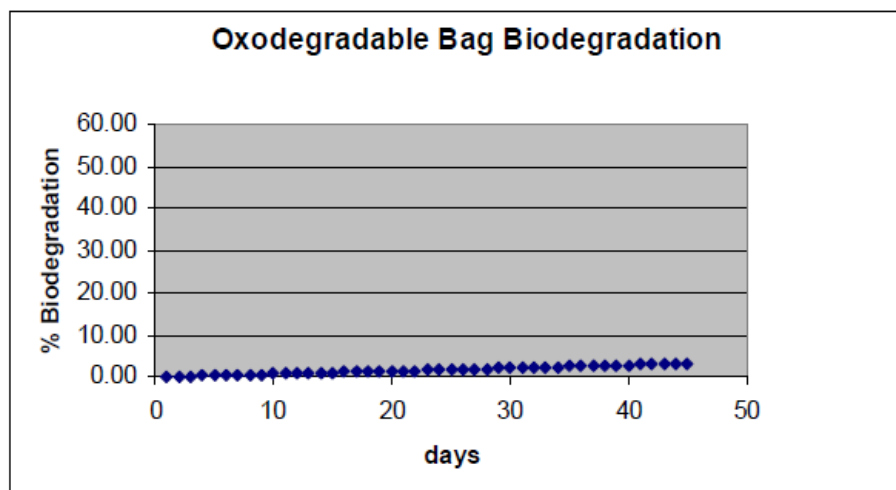


Figure 12. Result for 'oxo-degradable bag' tested by ASTM D5338 (laboratory biodegradation test).



Figure 13. Biodegradation apparatus for testing of biodegradable materials by ASTM D5338.



Figure 14. Cellulose positive control material before (left) and after (right) testing by ASTM D5338.



Figure 15. Oxo-degradable bags before (left) and after (right) testing by ASTM D5338.

Composting trials of Degradable Plastic Items

The biodegradable and oxo-degradable materials listed in Table 12 were tested in three composting environments including traditional windrow, in-vessel manure, in-vessel food waste, and in-vessel municipal solid waste. All of the compost facilities were commercial operations and produce compost for the public.

Table 12. Municipal composting facilities used for composting trials of compostable biopolymers and oxo-degradable bags²⁰.

Site	Output	Method
City of Chico Municipal Compost Facility	500,000 cu yds p.a.	Aerobic windrow composting
Vacaville Food-waste Compost Facility	30,000 tons p.a.	In-vessel composting
Mariposa County MSW Compost Facility	Not given	In-vessel composting

After the composting period, the materials were recovered where possible. In all four facilities, the PLA items and the Ecoflex bags had completely disintegrated. The results for the oxo-degradable bags in each study were as follows:

- City of Chico Municipal Compost Facility: “The oxo-degradable and UV-degradable plastics were completely intact and did not show any signs of disintegration”
- Vacaville Food-waste Compost Facility: “The oxo-degradable plastic bags, LDPE plastic bags and UV-degradable plastic bag did not appear to experience any degradation”
- Mariposa County MSW Compost Facility: “The oxo-degradable plastic bags, LDPE plastic bags and UV-degradable plastic bag did not appear to experience any degradation”

Photographs of oxo-degradable plastic items recovered from Composting Trials are shown in Figure 16 to Figure 18.



Figure 16. Oxo-degradable bag after 120 days in the City of Chico Municipal Compost Facility.



Figure 17. Oxo-degradable bag after 180 days in the Vacaville in-vessel compost facility .



Figure 18. Oxo-degradable bag after 170 days in the Mariposa in-vessel compost facility.

Bioaccumulation

This report did not evaluate bioaccumulation.

Environmental Impact

The University of California ²⁰ assessed the heavy metal content of the composts from the laboratory composting studies by analysing for lead (Pb) and cadmium (Cd) in all samples and additionally cobalt (Co) in the oxo-degradable compost. In the US the acceptable limits for Pb and Cd are 30mg/kg and 0.3mg/kg respectively, there being no limit for Co.

The compost samples were digested in nitric acid and the filtrate was analysed for the metals by atomic absorption spectrophotometry.

In all cases, the samples gave readings at or very near the lowest standard employed in each case. This meant that the lead and cadmium contents were well below the prescribed

limits while the cobalt content of the oxo-degradable compost was well below the detection limit.

Toxicological Impact

The University of California assessed the phytotoxicity of the composts from the laboratory composting studies by measuring tomato seed germination after ten days according to the method of ISO 11269. Ten seeds of tomato seed variety 'Tiny Tim' were planted in 50g samples of compost and germinated at 25°C and 80% relative humidity for ten days in ambient light. The germination index was determined from the product of percent germination and average seedling length. The results are shown in Table 13.

All the compost samples passed the phytotoxicity test; therefore the oxo-degradable compost did not show a phytotoxic effect.

This evidence is considered robust because an ISO standard procedure was followed. The investigators also tested the germination of cucumber and cress seeds and found them to have similar germination percentages to that of the tomato seeds although the seedlings lengths were more variable.

Table 13. Phytotoxicity of compost from laboratory composting experiments conducted by the University of California²⁰.

Material Average Germination %	Average Length, mm after 10-days	Average Germination Index	Average pH
46.67	24.33	11.35	8.5
43.33	22.67	9.82	8.8
83.33	18.33	15.27	8.7
66.67	26.67	17.78	8.4
70	25	17.50	8.63
70	20	14	8.5
70	14	9.80	8.77
60	32.33	19.40	8.63
63.33	16	10.13	8.83
56.67	18.33	10.39	8.6
73.33	18.33	13.44	8.8

Life Cycle Analysis

To date there is very little non peer-reviewed evidence pertaining to the Life Cycle Analysis of oxo-degradable plastics. An analysis of the peer-reviewed evidence has been given in Annex A.

6.9 Annex B2: Evaluation of Degradability by M J Carter Associates

In 2002 an additive manufacturer commissioned M J Carter Associates to “demonstrate that polyethylene manufactured with (their product) will mechanically and chemically break down over a short period of several months in a landfill environment”. All data in this section is taken from this report³⁶.

The tests were performed at the Edwin Richards Quarry Landfill Site near Birmingham (UK). The experimental plot dimensions were 30m by 20m.

The test material and a control polyethylene sheet containing no additive were tested by laying alternate layers of biodegradable waste and the test sheets until a minimum of 5 sheets had been laid. The site was then covered with non-degradable waste material. The temperature of the waste pile was monitored by several electronic probes.

The test pile was constructed the week commencing 22 January 2001 and samples were recovered by small excavation on six occasions: 28 February 2001; 4 May 2001; 16 July 2001; 21 August 2001; 2 November 2001 and 7 March 2002, fourteen months after the start of the trial. The longest interval was therefore 4 months, between the last but one sample and the last sample.

Except for the samples recovered in November 2001 and March 2002 which were tested for melt flow index (MFI) only, the recovered samples were tested at the laboratory for mass per unit area (BSEN 965), tensile strength (ASTM D638) and melt flow index (ASTM D1238).

The report states that there was significant variation in the condition of recovered samples and attributed this to the effects of the landfill environment. The temperature is also cited and the report states: “The laboratory data shows that there was no significant difference between the test and control samples collected from the waste up to and including the sampling visit in August 2001 consistent with temperatures in the waste below the critical temperature of 30°C”. The critical temperature in this case refers to the minimum temperature required to initiate the degradation process. It is not stated in the report why this was regarded as the critical temperature and it should be noted that, in the other work cited in this review (e.g. (Jakubowicz (2003) ¹⁸), the temperature used is 70°C instead. If 30°C is in fact the activation temperature, then this raises the question as to what happens to oxo-degradable plastics in service at ambient temperatures in the Tropics or the Middle East.

With regard to the “critical temperature” it is reported that the temperature of 30°C was reached at one probe between the 18 and 30 May. This probe was near a gas vent which was conveying warm air. On the 24 September 2001 the recorded average temperature was 30.7°C, with 7 of the probes exceeding 30°C. By the 2 November 2001 the temperature of 30°C was exceeded at ten of the probes.

The melt flow index was used to evaluate the degradation. The melt flow index increases as the polymer degrades and the molecular weight drops. Thus melt flow is a crude indicator of molecular weight which can only be used in a comparative way, i.e. a degraded polymer can only be compared with its undegraded form; it cannot be used to compare different polymers.

The melt flow indexes of the original samples were 0.76g/10min (control) and 0.75g/10min(test). The results are summarised in Table 14. The report states that “Four of

the nine melt flow index values for the test samples collected in March 2002 exceed the maximum melt flow index recorded for the pink control samples throughout the test period". No account is given of the properties of the remaining five samples which presumably had melt flow index values lower than the control.

The authors gave no explanation as to why the melt flow index had dropped between November 2001 and March 2002.

Table 14. Melt flow index values of control polyethylene and degradable polyethylene recovered from a landfill site in Birmingham UK between Jan 2001 and March 2002³⁶.

Date	Control Samples	Test Samples
22 Jan 2001 (start)	0.76	0.75
November 2001	1.11	13.27
March 2002	0.4	1.42

The additive producers analysed the samples by Fourier-Transform Infrared Spectroscopy and reported the appearance of a peak at 1715cm^{-1} (indicating oxidative degradation) in the samples recovered in November 2001. This peak was absent in the control samples and the oxo-degradable samples at the start of the trial.

RAPRA Technology Limited determined the molecular weight of four of the samples: Original control polyethylene; oxo-degradable polyethylene; recovered control polyethylene and recovered oxo-degradable polyethylene (both recovered in November 2002). While the original samples and the recovered control samples had near-identical molecular weight distributions ($M_w = 106,000 - 115,000$); the oxo-degradable polyethylene recovered from the landfill trial had a significantly reduced molecular weight (4,250-4,280).

There is no molecular weight data given for the samples collected in March 2002. Tensile tests were not done because the samples were distorted as a result of stretching and compression in the landfill environment.

The final conclusion of the report was that the melt flow index data, infra-red spectroscopy data and molecular weight determinations showed that following the onset of elevated landfill temperatures above 30°C the test plastic material began to degrade significantly compared to the control material.

It was also concluded that the shallow burial depth delayed the onset of the elevated temperature necessary and that optimum degradation conditions would be reached more rapidly.

6.10 Annex B3: Testing carried out at the Composting Plant at Vienna Neustadt in Austria.

A study was commissioned by two European companies. The authors were Prof. Univerz.-Doz. Dr. Bernhard Raninger and Dipl.-Ing. Gottfried Steiner⁶¹.

The purpose of the study was a full-scale evaluation of degradable polyethylene containing a manufacturer's additive in a municipal composting plant at Vienna Neustadt in Austria. This plant is designed to produce a compost product intended for garden and landscaping use. The process is in two stages: 2 weeks in an in-vessel forced aeration "tunnel" (60 tonne capacity) followed by a longer maturation period in an outdoor triangular windrow according

to Austrian National Standard ON S 2200. The study evaluated the effect of the material on the composting process and the final compost.

The report also refers to “DIN V 54900-3 (1998): Testing of the compostability of plastics - Part 3: Testing under practice-relevant conditions and testing of quality of the composts.” This standard has been withdrawn.

The sample was tested in one of the three units and was added at the rate of 1% by weight of compostable material. Prior to composting, the material had been stored outdoors to simulate compost bag storage and handling prior to disposal.

The film was evaluated after the 2-week tunnel process; again after 12 weeks maturation in the windrow and finally after 6 months.

The conclusions from the test were as follows:

- The presence of 1.1% by weight (660kg) of oxo-degradable PE in the test batch had no deleterious effect on the composting operation.
- After 26 weeks of bio-processing the end product fully met the Austrian Compost Quality standard.
- The authors report that more than 60% biodegradation was achieved in 26 weeks.
- The compost showed minimum or no trace of heavy metals and passed plant tolerance and seed germination tests (ON S 2023 as required by ON S 2200).
- The compost was tested at the OWS labs in Gent, (B) and showed no negative effect on cress germination, summer barley plant growth, daphnia and earthworms.
- The polyethylene containing the oxo-degradable additive met the new Austrian draft Compost Ordinance.

The report's final conclusions were:

- a) that the product met the requirements to be classified as a degradable / compostable plastic and the compost was fully acceptable as a land fertiliser.
- b) that the product may be considered to degrade successively by abiotic and biological pathways in a manner that produces no harmful or toxic by-products and are suitable for disposal in the environment.

However, in a later report of this study, the authors stated, “A final degradation rate of 63% is achieved in 26 weeks, failing to pass ballast matter limiting standards. (The manufacturer's) material easily disintegrates during composting, but does not meet of the requirements of CEN prEN 13432. (The manufacturer's additive) -based olefins would not pass the pre-norm prEN 13432 (1998) requirements concerning biodegradability. Due to the environmental condition during the decomposition period of 6-12 months, the material will not release 90% of TOC as CO₂, to be classified as biodegradable.”.

There is therefore some uncertainty as to the meaning of the results of this trial.

6.11 Annex B4: Results of a Landfill trial in Wisconsin conducted from 2005 to 2006

Some photographs are presented of compost piles containing oxo-degradable polyethylene bags. Although the provenance of the bags is not known, it is understood that these photographs were communicated to Prof. E. Chiellini in evidence of their performance in windrow composting.

It is understood that the photographs show the state of the windrows in May 2006, presumably after a typical composting period.

Figure 19 shows a general view of the windrow pile, Figure 20 and Figure 21 are closer views of the pile while Figure 22 and Figure 23 show the composting site after the windrow has been cleared away. It can be seen in Figure 19 that many bags are largely intact. Shreds of bag material were visible on the site after the windrow had been cleared (Figure 22, Figure 23).



Figure 19. Windrow composting site containing oxo-degradable polyethylene bags in May 2006



Figure 20. Windrow composting site containing oxo-degradable polyethylene bags in May 2006



Figure 21. Windrow composting site containing oxo-degradable polyethylene bags in May 2006



Figure 22. Windrow composting site containing oxo-degradable polyethylene bags in May 2006



Figure 23. Windrow composting site containing oxo-degradable polyethylene bags in May 2006

A similar result was experienced at a composting facility in Brynmawr, Wales when 'degradable' bags were used for collection of garden waste⁶². The resulting compost did not pass the criteria of PAS100 and was therefore rejected for use as compost. The rejected compost and oversize bag fragments had to be consigned to landfill at a cost of £61/tonne. The composting facility subsequently changed their policy to allow only certified 'compostable' bags and since then have not had any recurrence of the problem.



Figure 24. Rejected 'degradable' bag shreds from a composting facility y in Brynmawr, Wales.

Annex B5: Examination of Supporting Evidence for Claims Made on a Company website

The following are the claims have been taken from an additive producers website. All specific references have been removed, with the aim of providing an illustrative example of the type of claims made by the sector. Each marketing statement included in the table below is coupled with an analysis of the evidence to support it.

Claim no.	Nature of marketing claim made	Analysis of supporting evidence against each claim
1	The * additive is an additive formulation that renders conventional polyolefins oxo-degradable	None given
2	“Oxo-biodegradation” is “degradation identified as resulting from oxidative and cell-mediated phenomena, either simultaneously or successively”	Consistent with the citation
3	Plastic products made with the * additive will abiotically degrade in the presence of oxygen.	RAPRA report 46095 ⁶³ is offered in support of the claim of degradability in accordance with ASTM 6954-04. The conclusions from report 46095 is “That data obtained has demonstrated that the presence of the 181293224 masterbatch has speeded up the degradation of the LDPE material when subjected to either heat ageing at 70°C or when exposed to UV radiation.”
4	The ability of * products to comply with the biotic (biodegradation) tests has been demonstrated by the loss of molecular mass achieved after abiotic thermal degradation, resulting in ultimate biodegradation of the material into CO ₂ , water, mineral salts and biomass	RAPRA report 46303 ³⁷ is offered in support of the claim of compliance with ASTM 6954-04, which stipulates that the molecular weight should be less than 5,000 after degradation. This report confirms that the molecular weight of one LDPE sample was less than 5,000 after heating for 7 days at 70°C. The molecular weight of another sample was greater than 5,000 after heating for 9 days at 70°C. The molecular weight of another sample was greater than 12,000 after treating with ultra-violet light for 7 days. The intensity of the UV light was not stated in the report. Pyxis Report dated 30th July 2005 ⁶⁴ is cited in support of claim 4. This report described electron microscopic examination of ODPE samples “which had already begun to show signs of oxodegradation(sic)” following one of two treatments: samples were placed in wire cages which were then “immersed in water under a cascade in a pool containing fish” for thirty days. The role of the fish in the experiment was not explained. Samples were mixed with “typical garden compost” and incubated at 45°C for thirty days. ASTM D6954-04 states under ‘Significance and Use’ that: “The results of laboratory exposure cannot be directly extrapolated to estimate absolute rate of deterioration by the environment because the acceleration factor is material dependent...However, exposure of a similar material of known outdoor performance, a control at the same time as the test specimens allow comparison of the durability relative to that of the control under the test conditions”. The summary of the report states, “It was found that the surface of the plastic was colonised by microorganisms and that there was evidence that these microorganisms had removed mass from the plastic within the time frame of the experiment. It can therefore be concluded that given a longer period of immersion this plastic can be expected to fully biodegrade in these environments”. A control of known outdoor performance was not tested. ASTM D6954-04 states under ‘Scope’ that “accelerated oxidation data

must be obtained at temperatures and humidity ranges typical in that chosen application and disposal environment, for example in soil (20°C to 30°C), landfill (20°C to 25°C) and composting facilities (30°C to 65°C)". It is not clear from the claim or the cited documents how thermal treatment at 70°C for 7 days complies with the standard, given that the soil temperature to 15-20cm is usually that of air temperature. It is also not clear from the Pyxis report which of the referenced reports in ASTM D6954-04 is being addressed by the microscopic examination. See also the comments below in the analysis of Claim 10.

- | | | |
|---|--|---|
| 5 | The eco-toxicity sections of EN 13432 and ASTM 6954-04 require that no harmful residues are left – this has been verified for the * additive. (OWS Report MST-4/1). | OWS Report MST-4/1- (available online) is offered in support of claim 5. The tests were performed in accordance with EN13432. The conclusions from the test on additives * and * were that there is no toxic effect on either summer barley or cress. |
| 6 | The * additive does not contain heavy metals (defined by 92/64/EC Art 11 as lead, mercury, cadmium, or hexavalent chromium). | Supported by a statement by the manufacturers that the product does not contain lead, mercury, cadmium or hexavalent chromium. |
| 7 | The * additive is safe for direct food-contact according to the European Union requirements for Direct Food Contact 2002/72/EC and the US FFDC Act and regulations (RAPRA report 46137, and Keller & Heckman certificate 18.2.2009). It is the responsibility of the manufacturers of products intended for food-contact to ensure that all other materials incorporated by them comply with those requirements. | Supported by RAPRA report 46137 ⁶⁶ (available online) |
| 8 | If polymer products are correctly made with *, the additive will have no effect upon the strength and other performance characteristics of the product during its programmed service-life. | Supported by the manufacturer's own statement |
| 9 | Polymer products correctly made with * comply with the Essential Requirements of the EU Packaging Waste Directive 92/64/EC Annex II paras. 1,2 and 3(a) (b) and (d). | Has not been evaluated. |

- | | | |
|----|---|--|
| 10 | * oxo-biodegradable plastics are not currently intended for composting. | Supported by the manufacturer's own statement that these materials are not currently intended for composting. ASTM D6954-04, which is cited as supporting evidence by the manufacturer, refers to D5338 "Test method for Determining Aerobic Biodegradation of Plastic Materials Under Controlled Composting Conditions" and D6400 "Specification for Compostable Plastics". ASTM D5964-04 under "Significance and Use" states that " The correlation of results from this guide to actual disposal environments (for example agricultural mulch films, composting, or landfill applications) has not been determined, and as such, the results should be used only for comparative and ranking purposes." |
| 11 | If sent to landfill the * oxo-biodegradable plastics will degrade in aerobic conditions. In anaerobic conditions they become inert and will not emit methane. | This claim is an assertion by the manufacturers |
| 12 | * oxo-biodegradable plastics can be recycled together with ordinary oil-based plastics. For long-life products, stabilisers should be added if necessary. | |

Annex B6: Report on a Trial of Polyethylene Bags Containing Recycled Degradable Bags.

A report on the impact of biodegradable bags on recycling polyethylene bags was prepared by consultants for the Environment department of the province of Quebec in 2007⁶⁷.

In one experiment, unaged oxo-degradable polyethylene bags from two suppliers were combined with virgin polyethylene bags to make new material. In a second experiment, the oxo-degradable polyethylene was aged for 28 days before combining with the virgin material. Shopping bags were made from both batches. The effect of the unaged and aged oxo-degradable material on the processing stage and on the final bags was assessed in terms of the ease of processing and the performance of the bags. The performance was assessed by filling the bags with water and suspending them for over 100 days in a controlled environment.

The conclusions from this study were that oxo-degradable and conventional material were compatible in the recycling processing stage and there was very little effect of the oxo-degradable on the processing.

The shopping bags made from blends of unaged oxo-degradable and virgin material resisted water leakage for more than 100 days. This was true for blends containing up to 50% oxo-degradable material.

The shopping bags made from blends of aged (28 days accelerated weathering) showed a large loss of properties depending on the original manufacturer. Bags from “NeoSac” caused a severe deterioration and were considered to be incompatible, while the bags from the oxo-degradable polyethylene were considered to be compatible with the virgin polyethylene.

Annex C: Stakeholder views and claims

6.11.1.1.1 The identity of all of the individual companies who were consulted in this study have been omitted from the following sections and are denoted simply as the type of company followed by a letter, e.g. Additive Producer A.

6.12 C1: Additive Producers/ Masterbatch Suppliers

C1.1 Additive producer A

Type of communication: Email communication

Date: 17th February - 13th May 2009

Interviewer/author: Stuart Patrick, Loughborough University

It was stated that oxo-degradable plastics are generally used and promoted to solve the litter problem and so are normally used in single-use, short-life disposable packaging.

It was accepted that oxo-degradable plastics show a slower rate of biodegradation than most compostable plastics. However, it was believed that there are plenty of studies to show that they biodegrade to CO₂ and biomass.

A Life Cycle Analysis carried out in the USA on various bag types was referred to. The conclusion was that that PE type polymers (with or without a pro-oxidant additive) have by far the least environmental impact compared to compostable plastic and paper.

It was commented that there is controversy over the use of pro-oxidants with some aromatic polymers e.g. PS and PET as some toxic compounds are formed during degradation. It was also stated that pro-oxidant additives do not function with PC.

The level of degradation in landfills was said to vary, depending on the availability of oxygen.

It was claimed that oxo-degradable plastics are recyclable in existing recycling streams.

C1.2: Additive producer B

Type of interview: e-mail communication

Date: 3-8th April 2009

Interviewer/author: Stuart Patrick, Loughborough University

The interviewee confirmed that their oxo-degradable plastic product is based on transition metal technology and described how oxo-degradable plastics can undergo a process called oxo-biodegradation. Oxo-biodegradation is a two stage process in which a polymer is firstly converted by chemical reaction with oxygen to produce lower molecular weight chains. These shorter chains no longer behave as plastics and therefore the product fragments. These fragments, now chemically different, are available for biodegradation due to their lower molecular weight and greater degree of wettability, and can be ultimately converted into carbon dioxide, water and biomass, by micro-organisms.

Various standards relating to the oxo-biodegradation process were mentioned. ASTM D6954-04 is an international standard guide developed for 'Exposing and Testing plastics that Degrade in the Environment by a Combination of Oxidation and Biodegradation'.

Testing procedures described in Tier 1 and Tier 2 of ASTM D6954-04 represents the two stages of oxo-biodegradation. ASTM D6954 looks for a drop in weight average molecular weight to 5000 or less (from significant oxidation and chain scission of the polymer) and measures the time to reach 5% or less elongation to break. Samples of the participant company's oxo-degradable product were tested to the principles of Tier 1 of ASTM D6954-04, using UV irradiation as the initial degradation process. The results showed that the product met the expectation for the reduction in tensile properties, as the samples had broken by the end of the 14 days exposure time.

The safety of the product was illustrated in terms of approval for its use in food contact applications under the following regulations:

1. Europe

Polymer carrier is composed only from monomers and other starting substances from List A of Annex II to Directive 2002/72/EC, as amended up to and including Directive 2007/19/EC. There are no specific migration limitations. Other ingredients incorporated by CFN Packaging Group Ltd are positively listed under Annex III to directive 2002/72/EC and its amendments. These are no specific migration limitations. It is the responsibility of the manufacturer of the finished article to ensure compliance with Global Migration regulations.

2. USA

The Polymer carrier is in compliance with FDA regulations, Title 21 CFR 177.1520(c) 2.1. Other ingredients are permitted adjuvant substances as defined in 21 CFR 177.1520(b), for use in polyolefin food contact applications.

This producer also supplied a statement, dated November 2008, regarding REACH and Absence of Substances of Very High Concern (SVHC) in their masterbatch.

C1.3: Additive producer C

Type of interview: Telephone interview and email communication

Date March and August 2009

Author: Stuart Patrick

Producer C has developed an additive for oxo-biodegradable plastics that is claimed to enhance the "natural" degradation of agricultural plastic items. This producer is only concerned with the agricultural, horticultural and forestry applications of oxo-biodegradable plastics and is not involved with the packaging sector in this area.

There are different formulations available to suit the crop type and geographical locations in agricultural and forestry applications.

Their first application in the UK is growing quite fast and concerns oxo-biodegradable polyethylene mulch films for maize. The claim is that it allows maize growers to reduce significantly their impact on the environment when using degradable mulch due to less leaching of nitrates and obtaining better value from synthetic fertilizers or cattle manure/effluent.

For maize the film coverage is approx. 60kg plastic per hectare. When ploughed into the soil to 30 cm depth this equates to less than 20 ppm material. Visual scrap will disappear with no harmful substances being produced from the oxidised polyethylene.

Producer C believes that a key environmental advantage for maize grown under film in UK is the earlier harvest (up to 6 weeks).

- An earlier harvest gives farmers a much greater opportunity to establish another main crop before the winter (e.g. winter wheat) or a cover crop for the winter period (e.g. ryegrass). Also a greater opportunity to simply plough or cultivate the stubble. Both techniques are recommended by the Environment Agency to reduce soil erosion which is the singular main cause of diffuse pollution in UK water courses in dairy production areas.

- The earlier harvest leads to harvesting in drier conditions thereby reducing soil being dragged onto roads at harvest time. This in turn reduces top soil depletion and also the road safety problems that have been associated with the harvest of the UK forage maize crop.

Producer C also highlighted the general evidence (which is supported by well known science from various publications) for environmental benefits as follows:

- Water management: degradable mulch allows a regular supply of water to the crop by limiting evaporation and allowing earlier sowing (meaning fertilisation can occur before the dry period). Thus a reduction in irrigation can be achieved.
- Reduction in nutrient leaching such as nitrates due to surface protection
- Improved availability of other natural nutrients (P, K, Mg...) due to higher soil temperature and reduced consumption of the relevant fertilisers is possible.
- All of these factors also combine to give improved assimilation of organic fertilisers (manure, effluent).
- Higher yields per acre gives the possibilities of growing more biomass (i.e. higher biofuels capacity per farm) and so reduce the demand on fossil resources consumption

Further benefits can also be derived in Silage as follows

- Higher moisture and starch content has the effect of import of energy derived cattle food and reducing soya transport and associated production issues
- Healthier cattle with adapted feed stock results in less diseases with resulting less medicine consumption.

With regard to Grain:

- Less moisture results in less heat units consumed leading to a reduction in fossil resources consumption.
- Higher and richer content means less crop consumed by the starch industry.

One criticism of degradable mulch noted by producer C is the potential of soil erosion when crops are grown on steep slopes. Normally it is recommended to sow parallel to level curves (or to avoid mulching when this is not feasible).

Another criticism is the build up of oxo-bio film deposits in soil. Producer C believes that whilst more data could always be generated, the information from literature and actual experience must now be considered. In addition the mathematical model shows clearly there cannot be a build-up of foreign material in the soil year after year.

For information the mathematical model, that quantifies the amount of plastic in the soil, follows a rule that ensures the quantity cannot increase indefinitely but is limited to a maximum that is $U = U_0/q$ where U is the maximum quantity in the soil; U_0 is the annual quantity brought into the field and q is the minimum degradation rate per year.

Producer C commented that the French standard "Films de paillage en polyoléfinés additivées à durée de vie maîtrisée dans l'environnement pour l'agriculture et l'horticulture" is available to download from the AFNOR website.

Producer C also emphasised that data relative to composting are not relevant for degradation in the soil as physical and biological conditions are too dissimilar.

Producer C stated that standardisation of biodegradable material in soil is not as much advanced as it is for packaging articles destined for composting, due to the more complex nature of the topic.

The relevant CENTC249 WG9 is preparing a relevant document "Plastics to biodegrade in soil after use; characterization and format for reporting" that is still in enquiry but should be published shortly. An important point in the upcoming period will be to select the reference material (straw, natural rubber, other material?) that, compared to oxidised polyethylene, would lead to a relative biodegradation rate in soil up to 90% in a "reasonable" timeframe. Currently biodegradable polymer is accepted for composting when reaching a rate of 90% relative to cellulose in 6 months.

Further documents about the mulch and biodegradation process were subsequently supplied and these have been referred to in preparing this report.

C1.4: Producer D

Type of interview: Face-to-face interview and follow-up email communication

Date: 11th February 2009, 9th March 2009

Interviewer/author: Stuart Patrick, Loughborough University

The interviewee stated that there was much experimental evidence available to support Producer D's position that there were no environmental problems with their technology.

Producer D market around 40-50 product formulations in a masterbatch carrier utilising their additive technology based on carboxylic acid salts of Mn and Co. These metals are present in the form of metal ions which are necessary in human and plant nutrition and are acquired from food and water in the form of "essential minerals". These additives are marketed directly by producer D and through a network of licensees, sales agents and distributors in approximately 60 countries.

Using their know-how they can provide a customised formulation for a particular polymer, application and intended degradation time.

A draft standard capable of measuring oxo-biodegradation has been published by the British Standards Institution in 2007 – BS 8472. The French Standards organisation, AFNOR, published in July 2007 a Standard for oxo-biodegradable plastics in agriculture - XP T 54-980-1. Oxo-biodegradable plastic can be tested according to American Standard ASTM D6954-04 for Plastics that Degrade in the Environment by a Combination of Oxidation and Biodegradation. This standard guide provides a testing protocol using ASTM standard methods to compare the performance of plastics that biodegrade in various disposal environments.

A 2007 study by the Quebec government in Canada has confirmed that polyethylene bags incorporating one particular oxo-degradable additive are the only biodegradable bags tested that can be recycled successfully without any problems.

Copies of reports and studies were supplied by Producer D and have been used to prepare this report.

C1.5: Producer E

Type of Interview: Face-to-face

Date: 12th February 2009

Interviewer/author: Jane Clarke, Loughborough University

Producer E is a manufacturer of oxo-degradable plastic additives.

The history of the development of oxo-degradable plastics from which this producer's additive ultimately was developed was described. The interviewee was involved in initial research on oxo-degradable plastics in the early 70's. Research was carried out into the effect of different ion types (e.g. Ni, Zn, Co, Mn and Fe) as stabilisers for plastics exposed to UV. The research revealed that Ferric dithiocarbamate, far from stabilising, resulted in rapid degradation of the plastic when exposed to UV. Further research showed that all transition metal stearates had a photosensitising and destabilising effect on plastics. It was found that by varying the concentrations of Fe and Ni, the time over which degradation of the plastic took place could be controlled, given a constant amount of sunlight. Much of this work was carried out in Israel.

Producer E believes that the main oxo-degradable additive producers use the same technology of Fe stearate or Fe dithiocarbamates, possibly with some Mn salts. The additives are used in plastics at levels of about 0.01%. With regard to the amount of metal ions released into the environment following degradation, the researchers commissioned by Producer E concluded that the amount would not cause a significant increase above natural levels. The polymer itself is reduced to a fine powder with molecular weights of 5000 to 3000. It was believed that this powder would biodegrade.

Regarding the rate of degradation in the environment it was explained that this would depend on the amount and strength of sunlight. There is a recognised measure of UV radiation that hits the earth at different locations and this can be used to set the levels of radiation in a UV cabinet for laboratory studies. From producer E's studies it was concluded that, a carrier bag plastic containing an Fe pro-degradant would take the roughly the following times to degrade at different locations : Israel/Florida – 1 month, Spain -1 summer, England – 2 summers. They thought this makes the use of these additives unsuitable for plastic carrier bags in the UK. They also explained that since the degradation was autocatalytic, once exposed to sufficient radiation to start the process, degradation would proceed in the absence of light. This could translate to the environment where a plastic may be exposed on the surface for a while before being buried in landfill. They added that degradation would be quicker with a higher concentration of additive.

Producer E's own additive is not metal ion based but is ketone based and is purely organic. It can be used on its own or with the metal salt systems. The additive brings about degradation by the action of UV or heat, but they have not carried out biodegradation studies.

It is their view that oxo-degradable technology is complimentary to recycling and could be well applied where plastics are not recycled. One suitable application identified was that of industrial shrink-wrap packaging, since it is not recycled but goes to land-fill. They also thought that recycling of plastics was limited because recycled plastics could only be used for lower grade products. It was thought that oxo-degradable technology could be usefully applied to plastics that had already been recycled and were being used for their last functional life. They thought that contamination of a recycling stream with a small amount of oxo-degradable material would not have a significant effect, particularly because the additives would not interfere with stabiliser packages added to plastics.

Comparing oxo-degradable plastics to biopolymers which may be truly biodegradable, it was pointed out that the properties of biopolymers were not good enough to replace conventional plastics.

The application of oxo-degradable plastics in mulch film and tree protectors was considered particularly useful since the lifetime of the product could be tailored to the required life time and the levels of exposure to UV could be reasonably accurately estimated.

C1.6 Producer F

Type of Interview: Telephone

Date: 14th August 2009

Interviewer/author: Jane Clarke, Loughborough University

Producer F manufactures additive masterbatches that can be added to plastics that make them oxo-degradable. The following is a summary of the views of producer F expressed in an interview where the environmental impact of oxo-degradable plastics was discussed.

The overall benefit of using oxo-degradable plastics is that the excellent mechanical properties of conventional plastic such as PE and PP can be exploited while, by adding the degradable function, the negative effect of longevity of plastics in the environment can be removed.

The additives used in oxo-degradable packaging include pro-degradents which are transition metal salts, most commonly Fe, Co and Mn stearates. Fe generally has the greater UV sensitivity while Co gives both UV and thermal sensitivity. The other critical part of the system is the anti-oxidants and stabilisers which allow the materials to be processed and maintain their functionality for the time period required. A balance of stabilisers is required with phosphites generally being used for processing stability and phenolics for protection during the functional life of the product.

The way that the system works is that the stabilisers protect the plastic from oxidation, being used up in the process. During this time, when there is still any stabiliser present, the properties of the plastic remain the same and the plastic retains its functionality. When the stabilisers have been used up the pro-degradents are able to accelerate the oxidation of the plastic. The additive system is formulated to give a particular functional life after which degradation will begin, rather than specifying a particular time to complete degradation, which is difficult to predict. Functional lives of 18 to 24 months are usual for carrier bags, while 6 to 9 months may be required for bread bags.

Time to degradation is difficult to predict since this is so dependent upon the use history and disposal environment. For example, the material could be stored for most of its specified functional life before use, or it could be used straight away. Hence, even with the same disposal method, the time to degradation of these two materials would be different. In addition, the oxo-degradable plastic could be disposed of in many ways including; incineration, recycling, composting, landfill and it could be discarded as litter. All these environments are very different, having great variations in levels of UV light, and heat, which will strongly affect the rate of degradation.

Starting from an initial molecular weight of for example, 200 000, oxo-degradable PE and PP will degrade progressively, reducing molecular weight. As the molecular weight reaches about 100 000 the plastic will begin to fragment, smaller particles being produced as the degradation progresses further. After a molecular weight of about 5000 has been reached the material can be assimilated by microorganisms and biodegradation begins. The biodegradation is not fast enough for the material to pass the composting standard of

EN13432, where there must be 90% degradation in 180 days. It would take an oxo-degradable plastic about 18 months after fragmentation to reach this level of biodegradation. However, oxo-degradable plastics degrade more quickly in the in-vessel composting units that are suitable for the processing of animal waste because they operate at elevated temperatures (as required by the Animal By-Products Regulations).

Degraded oxo-degradable plastic was found to be non-ecotoxic when tested by an independent, accredited laboratory according to the 3rd part of the EN13432 standard. Any potential harmful effect of the plastic fragments in the environment should be less for the oxo-degradable plastics than conventional plastics since, providing there is a suitable environment, they will degrade and be assimilated more quickly than fragments of conventional plastics.

Oxo-degradable plastics can be recycled without loss of function (in terms of usability) as long as degradation has not started to take place. The oxo-degradable function will be maintained within the recycled material, although it may be diluted by the presence of non-degradable plastic.

It is recommended that the best disposal route for an oxo-degradable product, such as a carrier bag, should be re-use followed by recycling, as long as degradation has not started.

C1.7 Producer G

Type of Interview: Face-to-face, telephone and email

Date: 2nd and 6-7th April 2009

Interviewer/author: Stuart Patrick, Loughborough University

Producer G has spent many years developing a range of oxy-biodegradable additive masterbatches. These masterbatches use a different transition metal ion to those commonly marketed by their competitors and are formulated to have a technical superiority in terms of controllability and performance when it comes to the degradation profile.

Formulations are available for polyethylene (PE) and polypropylene (PP) and can be designed to suit the required shelf life and embrittlement time for the intended application, or to meet customers' aspirations.

Producer G supply their products globally with a wide range of applications, from check-out bags, agricultural mulch films, to single use films. One interesting application is in polypropylene tree guards where the customer requires a great deal of stability followed by rapid degradation. Their products have been formulated to offer a variety of dwell times followed by rapid embrittlement (first stage of degradation) rendering the smaller particles of reduced molecular weight oxidised species available for biodegradation.

The mechanism of the additive was described in terms of free-radical scavenging which decreases in efficiency once exposed to natural or UV light (photo-initiation). The first stage of degradation results in embrittlement. This is said to be followed by biodegradation once the polymer chain has been reduced to around 10,000 units.

Time to degradation is difficult to predict due to the sensitivity to environmental conditions. Producer G usually makes predictions of time to degradation assuming steady conditions of, for example 20°C with 12 hour days of "normal" sunlight. For time to embrittlement, feedback they have received agrees very well with the laboratory simulated testing, giving them confidence in house testing and the predictions which are derived from these results. Time to biodegradation is even more difficult to predict due to the additional uncertainty about the level and viability of the microbes in the medium surrounding the discarded product. Producer G try and speed up this secondary biodegradation stage by including a

biodegradation promoter in formulations which encourages the development of microbial colonies before the chain scission has occurred. Making the above assumptions they predict secondary biodegradation would normally fall into the 2 to 3 year range.

The producer provided reports and technical information sheets to support their claims regarding photo-initiation, biodegradation

Furthermore, they are confident that their technology permits recycling within the known shelf life of the material and can be added at a percentage of the virgin material. However no test data is available yet to confirm this aspect. The company has recently formed a strategic partnership with a PET bottling company. This has taken on the concept of the need to ensure that these bottles should be recyclable in the short term (two years) but can degrade in the land and marine environment over a longer time span (ten years) if the bottles miss out on the collection for recycling phase. Initial recycling tests have been carried out successfully.

The safety of the additives was addressed in terms of compliance with food contact regulations. The components within producer G's technology have safety approvals, including full compliance with CONEG (Coalition of North Eastern Governors-USA), FDA and EPA regulations for direct food contact. All components of the masterbatches being listed in European Directive 2002/72/EC (Food Contact Plastics). Therefore they can be used in plastic materials and articles intended to come into contact with foodstuffs. Migration testing should be carried out to demonstrate that materials containing their additives comply fully with these regulations. By virtue of their listing in the European Directive 2002/72/EC, the components these additives are unlikely to cause harm to humans when incorporated appropriately into polyethylene bags which are also used appropriately. It was added that the metal ion used within their system is ubiquitous throughout the environment and is naturally present in soil in very high levels. The masterbatch is added at very low levels in to the base resin in order to produce an oxo-biodegradable property and is typically in the region of 1%.

6.13 C2: Trade Associations in the Plastics Industry

C2.1: Packaging and Films Association (PAFA)

Type of Interview: Email communication

Date: 20th March

Interviewee/contact: Peter Ettridge

Interviewer/author: Stuart Patrick (Loughborough University)

A statement and two presentations were supplied and used in the preparation of the report. The following points were also made.

Oxo-degradable additives do not increase functionality in terms of sourcing, application or disposal of plastics. The only identifiable benefit is fragmentation of polyethylene disposed of in a marine environment or in the developing world where waste disposal systems are not sufficiently developed. It was also commented that the degradation of oxo-degradable plastics could result in slow burn in landfill, leading to instability and CO₂ evolution. 1 tonne of bags equates to about 1 car driven for 10,000 miles per year.

C2.2: Oxo-Biodegradable Plastics Association (OPA)

Type of Interview: Telephone and email communication

Date: August 2009

Interviewee/contact: Professor Gerald Scott

Interviewer/author: Stuart Patrick, Loughborough University

Professor Scott, DSc (Oxon), C.Chem, FRIC, FIMMM Emeritus Professor of Chemistry and Polymer Science, Aston University, UK is Chairman of the Scientific Advisory Board of the OPA. He has published many textbooks and research papers concerning polymer degradation and biodegradation. The OPA (www.biodeg.org) is an independent organisation which includes at least one additive manufacturer and more than 60 end-users from different parts of the world.

This report is based on an interview with Professor Scott supplemented with additional material supplied by Professor Scott and relevant material extracted from the OPA August 2009 Briefing Note and Position Papers available on the website.

The technology produces plastic which degrades by a process of oxo-degradation and is based on a very small amount of pro-degradant additive being introduced into the manufacturing process, thereby changing the behaviour of the plastic. Degradation begins when the programmed service life is over (as controlled by the additive formulation) and the product is no longer required.

The additives are based on compounds of the transition metals Fe, Ni, Mn or Co with Co being used widely in the packaging area. Fe and Ni are primarily used for mulch film. The actual content of metal in a salt is typically less than 10% with the addition level of the active ingredients being ~ 0.1% of the finished film. These transition metal salts are generally considered to be non-toxic.

In the first phase of the degradation process (abiotic under the influence of oxygen, sunlight and/or heat) the formulation breaks the molecular chains so that the material is no longer a plastic but a material of lower molecular weight compounds. The material does not just fragment, but will be consumed in the second phase by bacteria and fungi³ after the formulation has reduced the molecular weight to a level⁴ which permits living micro-organisms access to the carbon and hydrogen. It is therefore “biodegradable.”⁵ This process continues until the material has biodegraded to nothing more than CO₂, water, and humus, and it does not leave fragments of petro-polymers.

Oxidation by molecular oxygen is the rate controlling step and based on the research work of Professor Jakubowicz utilising Arrhenius plots, it has been estimated that, depending on the formulation/application the oxo-biodegradable plastic will biodegrade completely between two and five years. This is a much shorter time scale than many natural materials, e.g. straw, leaves, twigs, etc.

³ “Degradable Polymers – Principles and Applications” Kluwer Academic Publishers 2002; “Environmental biodegradation of polyethylene”, S.Bonhomme, A. Cuet, A-M.,Delort, J. Lemaire, M.Sancelme and G.Scott, Polym. Deg. Stab., 81, 441-452

⁴ sub 40,000 Daltons

⁵ Oxo-degradation is defined by TC249/WG9 of CEN (the European Standards Organisation) as “degradation identified as resulting from oxidative cleavage of macromolecules.” And oxo-biodegradation as “degradation identified as resulting from oxidative and cell-mediated phenomena, either simultaneously or successively.”

Degradation and biodegradation of an oxo-biodegradable polyethylene specimen consistent with changes expected by Tiers 1 and 2 of ASTM D 6954-04 has been found by RAPRA⁶ Oxo-biodegradable additive also passes the eco-toxicity tests prescribed by Tier 3 of ASTM D 6954-04, including seed germination, plant growth and organism survival (daphnia, earthworms).⁷

In rivers, lakes and oceans most oxo-biodegradable polyethylene films float on the surface, where they are oxidised with consequent fragmentation and biodegradation. There is oxygen and ultraviolet light on the surface, there are sufficient micro-organisms, and the wind and waves subject the material to stress. Even if the material sinks, and uv light is reduced, degradation will continue while oxygen is present. There are normally enough micro-organisms, and there may also be stress caused by sub-surface currents.

Appendix 1 lists the results of extensive research that has been carried out on potential eco-toxic effects of particulate and extensively degraded oxo-biodegradable plastics when mixed with soil.

The conclusion from the published work is that the four usual pro-oxidant transition metal ions (Mn, Fe, Co and Ni) are no more toxic in the environment than the abundant naturally occurring minerals and that on the contrary both are the source of essential elements for human nutrition.

Oxo-degradation is defined by TC249/WG9 of CEN (the European Standards Organisation) as “degradation identified as resulting from oxidative cleavage of macromolecules.” Oxo-biodegradation is “degradation identified as resulting from oxidative and cell-mediated phenomena, either simultaneously or successively.”

Oxo-biodegradable plastic is designed to degrade, then biodegrade, if it gets into the open environment. It is NOT currently marketed for composting, and it is not designed to degrade in anaerobic conditions e.g. deep in a landfill, where it remains inert and does not biodegrade to methane.

Composting is not the same as biodegradation in the environment due to the longer timescales of the latter process.

A draft standard (BS 8472) for oxo-biodegradation of plastics is being prepared by the British Standards Institution. Professor Scott chairs the working party and is hopeful that a draft will be ready for issue by the end of 2009. Straw will be used as the reference material against which the rate of polymer biodegradation will be measured.

The main benefit of oxo-biodegradability is not for plastic waste which is sent to landfill, but for plastic waste which gets out into the environment, where it will accumulate for many decades on land and in the oceans.

Some plastic waste will of course be collected and sent to landfill, but oxo-biodegradable plastic waste should not be sent to landfill at all. After collection it should be recycled, or incinerated for energy-recovery. OPA takes the position that it is better for the environment to re-use, recycle and incinerate to energy than to convert the carbon to CO₂

⁶ Tier 1 (Degradability) test 46023 20th March 2006. Tier 2 - (Biodegradability) test 46303 7th June 2006. RAPRA Technology Analytical Laboratories are accredited by the United Kingdom accreditation authorities as meeting the requirements of International Standards Organisation norm no.17025

⁷ Organic Waste Systems NV Belgium - Reports 1812/93224 8th Mar 2006. See also G. Scott and D.M. Wiles, *Degradable Polymers: Principles and Applications*, Kluwer, 2002, Chapter 13, Section 9.11, page 472, et seq.

during composting as required at present by international composting standards (e.g. EN 13432)

In the situations where oxo-biodegradable plastic does end up in landfill, decomposition deep in a landfill is not desirable. Whilst oxo-biodegradable plastics fragment and biodegrade in the upper layers of the landfill and emit CO₂ at a low rate there in the presence of oxygen, they are completely inert deeper in the landfill in the absence of oxygen.

The OPA supports the recycling of plastics and information is available in Appendix 2 which reinforces the fact that oxo-biodegradable plastics can be recycled together with other clean commercial polyolefin wastes.

However, there are some agricultural applications of oxo-biodegradable plastics in which the waste plastic cannot be recycled for logistical reasons. For example the collection of used mulching film litter for the fields is costly because it is spread over extensive areas as contaminated residues which are energy expensive to cleanse for reprocessing. This was the main reason that oxo-biodegradable polyolefins replaced regular plastics because they can be simply ploughed into the soil where biodegradation continues without any adverse effect on subsequent crop yields.

Appendix 3 highlights the requirement to add more stabiliser and antioxidant prior to recycling clean oxo-biodegradable plastic. It is also reported (S. Al-Malaika, et al., Recycling Degradable Polyethylene, *J. Macromol. Sci. Pure App. Chem.* (1995) A 32 (4) 731) that oxo-biodegradable plastics that have not had a severe exposure to the environment can stabilise the mixed recycle.

Ecotoxic Effects

The OPA state that extensive research has been carried out on potential eco-toxic effects of particulate and extensively degraded oxo-biodegradable plastics when mixed with soil. Tests included seed germination and plant growth rates, compared with the same soil without degraded plastics [3,4], the effects on macro-organisms (worms, daphnia, etc.) in the soil [4] and on the accumulation of transition metal ions in the stems, leaves and fruit of plants during the growing season [2,5].

With the present range of degradable plastics which incorporate fractions of a percent of transition metal ions, as indicated above, there are no negative effects shown by any of the above tests. It is also recognised in horticulture that fragmented oxo-biodegradable plastic films play a positive role as soil conditioners [6].

The commonly used transition metal compounds in commercial oxo-biodegradable plastics are manganese, iron, cobalt and nickel. As indicated above, none of these are "heavy metals" and none have been shown to be eco-toxic.

Indeed, all the above transition metal ions are required in human and plant nutrition, and are absorbed from foodstuffs and water. Far from being dangerous they are considered to be "essential" minerals required in oxygen transport systems. The non-toxicity of iron, which is present in blood haemoglobin, catalase and peroxidases and of manganese, required for manganese peroxidase, have never been questioned [7].

The UK Food Standards Agency has carried out a risk assessment [8] on trace elements, and the following is a summary of their findings.

High concentrations of cobalt are normally found in fish (0.01 mg/kg), nuts (0.09 mg/kg), green leafy vegetables (0.009 mg/kg) and fresh cereals (0.01 mg/kg). Most of the cobalt ingested is inorganic. Fresh water concentrations of Co range from 0.001 to 0.01 mg/L. The mean population intake of Co is 0.012 mg/day. Cobalt is also included in some multi-constituent licensed medicines, at a maximum daily dose of 0.25 mg. Although cobalt is an essential trace element, Co deficiency has not been reported in humans (presumably because of its widespread availability from food and water).

Gastrointestinal absorption of cobalt depends on the dose. Very low doses are almost completely absorbed, whereas larger doses are less well absorbed. Most excess cobalt is excreted in urine. The only toxicity data for cobalt reported in the literature was in 1960, when heavy beer drinkers suffered cardiomyopathy as a result of the use by the brewing industry of cobalt chloride as a "foam stabiliser" at (1.0-1.5) mg/kg. Ethanol and cobalt have a synergistic effect in reducing blood flow causing damage to the heart. Massive doses of cobalt salts (30 mg/day), evaluated as a treatment for anaemia's led to skin rashes and hot flushes. Prolonged use of cobalt "therapy" led to depression in iodine uptake.

Nickel is present in a number of enzymes in plants and micro-organisms and in humans it influences iron absorption and metabolism. It is found in a variety of foods as ionic Ni, particularly in pulses and oats (0.18 mg/kg in miscellaneous cereals), and in nuts (1.77 mg/kg). Lower levels are found in water. Total intake of nickel by humans from all sources is up to 0.26 mg/day and no potential high intake groups have been identified. The average intake from food and drinking water is 0.16 mg/day. Nickel is excreted in urine and in sweat.

Acute nickel exposure is associated with nausea, vomiting abdominal discomfort and diarrhoea. The lowest reported oral dose associated with acute effects of nickel in humans was 1.2 mg in a 60 kg adult. Chronic inhalation of nickel and its compounds is associated with lung cancer in humans and in animals but orally administered nickel was found not to be carcinogenic. It was the exposure of humans to nickel during mining that led to the believe that nickel is carcinogenic however it is imbibed but administration of nickel compounds orally has shown that the main effects in humans is in skin sensitisation but only over 5.6 mg.

From the above, it can be understood how and why the common transition metals are obtained by humans as essential nutrients. It will also be useful when discussing "dangerous substances" in the environment to see how they are absorbed into the food chain from the soil. In fact, the amounts of transition metal ions available to plants from common soils is much higher than can be absorbed by the plants [2] and is very much greater than would be produced from degradable plastics in the soil.

Particular attention has been paid to cobalt and nickel for the reasons discussed above. Volcanic soils contain very high concentrations of cobalt oxide (up to 100 ppm) and nickel oxide (up to 750 ppm). Sandstone and limestone contain 90 ppm and 10-20 ppm of nickel respectively [2]. However, the amount of nickel taken up by the plant appears to have little to do with its concentration in the soil.

Table 1 shows the effect on plant uptake of nickel sulphate applied to the soil to simulate the deposition of nickel from degradable polyethylene mulching films by up to 180 years of application to the same soil [2]. It is clear that the accumulation of nickel in various parts of the plant remains constant within experimental limits, whatever the concentration of nickel in the soil.

Furthermore, It can be calculated that in the 'worst case scenario', it would take 500 years to increase the nickel content of soil using typical nickel contents of degradable polyethylene mulching films by 1 ppm [1].

Table 1 - the accumulation of nickel in melons (ppm, measured by atomic absorption) grown in soils containing increasing amounts of nickel sulphate¹ [25]

	Control	60 years	120 years	180 years
leaves	17.3	15.2	13.5	13.7
stems	5.0	4.5	5.2	5.0
flesh	2.7	2.0	3.0	3.2
skin	3.0	3.5	3.2	3.0

¹The soil was sprayed with NiSO₄ to give nickel concentrations in the topsoil equivalent to the accumulation from S-G mulching films used for the number of years indicated.

Conclusion

Synthetic hydrocarbon polymers (e.g. polyolefins, polystyrene and synthetic rubbers) biodegrade in the environment by the same abiotic and biotic processes as naturally occurring polymers (e.g. natural rubber, resins and lignin).

In the case of conventional commercial plastics the rates of formation of oxidation products depend on the presence of pro-oxidant transition metal ions (Mn, Fe, Co, Ni) and commercial antioxidants. The lifetimes and hence biodegradation times of commercial biodegradable polyolefins may vary by orders of magnitude depending on the application. The time-scale from the end of the user life to final conversion in the environment to carbon dioxide, water and biomass lies within the range of many natural product wastes such as straw and related lingo-cellulosic materials.

The oxidation products of both natural and synthetic hydrocarbon polymers biodegrade rapidly and are absorbed by microbial cells. Consequently, abiotic or biotic oxidation is normally rate controlling and there is no accumulation of low molar mass products in the environment.

The rates of abiotic peroxidation of carbon-chain polymers in the environment can be predicted from laboratory tests and it has been shown that the biodegradation rates of the oxidation products correlate with mass loss of the polymer. The purpose of eco-toxicological tests is to ensure that neither the fragmented polymers nor their oxidative breakdown products have an adverse effect on plants or to humans and animals that may consume the crops.

It is clear from the published work that the four usual pro-oxidant transition metal ions (Mn, Fe, Co and Ni) are no more toxic in the environment than the abundant naturally occurring minerals and that on the contrary both are the source of essential elements for human nutrition.

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Recycling

The length of the useful life of an oxo-biodegradable plastic product is determined by antioxidants (processing stabilisers and UV stabilisers) contained within the formulation, which can be modified so that the plastic product degrades according to whatever timescale is required.

Obviously if any plastic is going to be recycled it will have to be collected and recycled before it has become embrittled. Oxobiodegradable products will normally have a useful life before embrittlement of at least 18 months, and if they have not been collected and recycled by then, they probably never will be.

New oxo-biodegradable products made with recycle

If a new product is to be made with recycled polymer which contains or might contain a pro-degradant formulation and the new product is intended to be degradable, the process is obviously straightforward, as a pro-degradant effect is actually desired. This applies particularly to recycling of oxo-biodegradable offcuts in plastic factories, or where used oxo-biodegradable “back-of-shop” plastics (e.g. shrink-wrap pallet-wrap, bread-wrapping etc) are sent back for recycling into more oxo-biodegradable products.

Short-life products

If the new product to be made from recycle which contains or might contain a pro-degradant formulation, is intended for short-life products such as refuse-sacks, bin-liners, shopping bags, bread wrappers etc. the effect of any pro-degradant formulation is unlikely to manifest itself during the intended service-life, and biodegradability for such items is in any event desirable. It is desirable because a proportion of these items will always find their way into the land or sea environment, where they would otherwise subsist for decades after they had been discarded.

Long-life products

Since polymers lose stabilisers every time they are reprocessed, it is good practice to add new stabilisers each time, whether the feedstock contains oxo-biodegradable plastic or not.

If suitably formulated, the stabilisers will also neutralise any pro-oxidant which may still be effective.

Building Films

If the new product to be made is a plastic film intended for long-term durability - such as a building film for damp-proofing or waterproofing - the specification in some countries for some of these films requires the use of a virgin polyolefin compound ⁸ and recyclate is not therefore relevant. For all other building films the specification will usually require the use of stabilisers where necessary.⁹ There will of course be no pro-degradant formulation in recyclate chosen from in-house scrap, or from other feedstock whose origin is known.

In the case of lower-grade building films, where no guarantee is given, these are often made from recyclate whose origin is not known, and the manufacturer should always add stabilisers as above, whether the feedstock contains a pro-degradant formulation or not.

Pipes

(a) ISO Standard 8779 "Plastics piping systems — Polyethylene (PE) pipes for irrigation" provides at para. 4.2 that only clean reprocessable material generated from a manufacturer's own production may be used if it is derived from the same resin as used for the relevant production. As the origin of the material will be known, it will not therefore be used for this purpose if it could contain any pro-degradant formulation.

(b) SABS ¹⁰ piping is manufactured to a specification which permits the use of recyclate only from "in-house scrap." Small bore piping class 6 and 10 is usually LDPE and, larger sizes, HDPE.

"In-house scrap" is scrap which has been generated during manufacture of the SABS grade pipe which can be chipped up and added back.

There is therefore no difficulty with the manufacture of such piping, as the origin of the recyclate is known and it will not therefore be used for this purpose if it contains any pro-degradant formulation.

(c) "SABS Equivalent" piping is manufactured from 100% recycled material according to the SABS specification but is not marked. Usually HDPE with from 5-20% LDPE blended for flexibility. For a quality product where a guarantee is demanded, clean industrial scrap is used where product history (material source and material grade) is known. This will not therefore contain a pro-degradant formulation.

(d) Agricultural and Domestic piping is manufactured in South Africa from 100% LDPE scrap. Normally the same scrap is used as in (c) above, but it should only be used in low-tech situations if the origin of the recyclate is unknown. Stabilisers should always be added if there is any doubt about the origin of the recyclate, and there is a case for an industry specification for this category of piping, which would include a requirement to add stabilisers.

⁸ Eg South African Bureau of Standards Specification 952-1985 para. 3.2.2

⁹ South African Bureau of Standards Specification 952-1985 para. 3.2.1

¹⁰ South African Bureau of Standards

“Low tech situation” refers to small bore piping Class 3 and 6 used for piping water to cattle or game troughs or on domestic irrigation systems, essentially at low pressures.

Recycling of Oxo-biodegradable Plastics - Gerald Scott, Professor Emeritus in Chemistry and Polymer Science, Aston University

Oxo-biodegradable plastics are manufactured by the addition of prooxidant additives during formulation. Without the addition of stabilisers to protect against environmental peroxidation, the oxo-biodegradable plastic item rapidly loses its mechanical properties. However this process is delayed by the antioxidant/stabiliser combination, which retards the onset of the degradation process and during this time the antioxidant system is removed.

So long as the stabiliser system is still present, virtually no change in properties can occur and the waste polymer can be recycled to the original oxo-biodegradable plastic by the addition of the same stabilising system. If more durable products are required this can be achieved by further addition of stabilisers. This is called “closed-loop” recycling and it can in principle be repeated many times.

In practice, waste oxo-biodegradable plastics are frequently reprocessed together with regular commercial plastics wastes of similar structure, which may contain a variety of stabilising systems and the durability of the recyclate will depend on synergistic or antagonistic effects on durability. This applies irrespective of the presence or absence of oxo-biodegradable plastics and interestingly, it has been found that oxo-biodegradable plastics that have not had a severe exposure to the environment actually stabilise the mixed recyclate¹¹.

Conclusions

- 1 Oxo-biodegradable plastics can be recycled in a closed loop to the original application by addition of appropriate processing and weathering stabilisers
- 2 Oxo-biodegradable plastics can be recycled with co-mingled generic commercial plastics waste by normal reprocessing procedures

April 1 2009

¹¹ S. Al-Malaika, S. Chohan, M. Coker, G. Scott, R. Arnaud, P. Dabin, A Fauve and J. Lemaire, *J. Macromol. Sci., Pure & App. Chem.* A32 (4) 731 (1995)

6.14 C3: Retailers

Several of the major multiple retailers were contacted to determine their opinions on the use of oxo-degradable plastics in packaging. The views of all those that responded are summarised below.

C3.1: Retailer A

Type of Interview: Email communication

Date: 4th March

Interviewer/author: Stuart Patrick (Loughborough University)

Retailer A considered using ox-biodegradable plastics in the past and ran a trial on them. However, it was decided not to use them. The oxo-biodegradable films ran well on the lines and performed in-store with no problems. They were also cost neutral. However there were concerns about their environmental impact and their breakdown in anaerobic landfill. Starved of oxygen and light it was considered unclear what actually happened in the degradation process. It was concluded that even if fully degraded, the same plastic remains, just in smaller pieces. It was acknowledged that the decision was slightly subjective due to the lack of research and scientific fact to base it upon. Instead of following this route, the retailer focused on light-weighting, de-layering, improving recyclability and driving for sustainable sources. Finally it was commented that they would be keen to see the outputs of any formal research project into this area.

C3.2 Retailer B

Type of Interview: Email communication

Date: Between 5th and 27th February

Interviewer/author: Stuart Patrick, Loughborough University

Retailer B has a packaging policy which states that materials that interfere with an established recycling stream will not be used. This is one of the reasons that Retailer B does not use polylactic acid (PLA) in hard plastic packaging and especially not in bottles as it contaminates PET recycling. This retailer uses oxo-degradable plastics in packaging because they do not interfere with such recycling streams.

It was considered that the use of degradable technology is not a perfect solution but a useful stepping stone. It was added that if widespread recycling of polythene films were to take off in the UK, there would be no point in making it degradable.

Retailer B has been given scientific papers that demonstrate the use of the technology, but has left the additive manufacturers to supply this sort of information. However, one of the pieces of information considered particularly relevant was the fact that the first phase in a landfill is actually aerobic and very hot.

This retailer has carefully considered the claims on oxy-biodegradable plastic packaging. Examples are given below:-

The text on the bags for sliced bread is:

"Degradable Packaging: This bag will fully degrade to carbon dioxide, water and a small amount of inorganic residue after approximately 4 years in the domestic waste stream. This compares to conventional plastic taking over 100 years to degrade."

Retailer B believes that the following is the statement that should be used on EN13432 materials which are not also home compostable:

"INDUSTRIALLY COMPOSTABLE. This packaging has been tested to compost within 16 weeks in optimum conditions in an industrial, animal by-products licensed composter. Currently, only 50 suitably licensed composters operate in the UK, and we are only aware of one local authority who might collect this packaging for treatment."

A reference regarding landfill conditions was also provided.

C3.3 Retailer C

Type of Interview: Email communication

Date: 25th March

Interviewer/author: Stuart Patrick, Loughborough University

Retailer C have sustainability aims outlined in their packaging charter. On this basis this retailer has based their carrier bag policy on (i) promoting re-use and (ii) maximising the % of recycled polythene. They do not use paper due to the much higher carbon footprint. Oxo-degradable plastics are not used on the basis that (i) they can contaminate traditional recycling (ii) they do not save landfill in the timescales they degrade and (iii). they can 'greenwash' consumers into believing that not re-using carrier bags is acceptable. Retailer C made reference to a report by Waste & Resources Action Programme (WRAP) carrying out some work on oxo-degradable plastics in 2007 which also concluded against their use based on environmental impacts.

C3.4 Retailer D

Type of Interview: Telephone

Date: 20th May 2009

Interviewer/author: Stuart Patrick, Loughborough University

retailer D's focus is to reduce overall the number of plastic bags given out by promoting the use of re-usable bags and giving out bags only on request and so reduce the impact on the environment. They have moved from 78% virgin polymer content to 50% content at the start of 2009. Reduction in the gauge of carrier bags also means that, over the year, 1000 tonnes less plastic will end up in landfill.

A new oxo-biodegradable formulation has been developed in cooperation with an oxo-degradable plastics producer, which is designed to degrade more quickly (<12 months). This is aimed to tackle the littering problem and to reduce the impact on landfill. The evidence seen by retailer D confirms that this formulation will be ultimately biodegradable. The retailer also raised the issue of incineration and believes that there should be an open debate to consider it as a potential alternative to landfill and address the wider concerns of waste. Other countries in Europe are much further ahead in this area.

6.15 C5: Agricultural and Horticultural Applications

C5.1 Environment Agency

Type of Interview: email communication

Date: 12th May

Interviewee: Simon Barron, Agricultural Technical Advisor (Agricultural Waste), Environment Management Technical Services

Interviewer: Jane Clarke, Loughborough University

The Environment Agency does not accept the ploughing in of oxo-degradable plastic mulches because it is not considered beneficial or environmentally benign. The decision was based on the results of a literature search and peer review into the composting of oxo-degradable plastics.

C5.2 National Farmers Union (NFU)

Type of Interview: Telephone

Date: 6th May 2009

Interviewee : Aaron Naik, Environment Policy Advisor, NF

Interviewer/author: Jane Clarke

The use of oxo-degradable plastics in agricultural applications is not widespread in the UK. However, the development of oxo-degradable plastics is known about, together with an appreciation of the controversy surrounding their use. In the absence of direct knowledge of the use of oxo-degradable plastics on farms, the potential effects and farmers' concerns were discussed.

Farmers suffer from having relatively small amounts of widely dispersed plastic that needs to be collected and disposed of. A potential advantage of the oxo-degradable plastics is that they could be disposed of in-situ, thus avoiding the need for collection, with its attendant financial and environmental costs. Similarly, costs of final disposal in landfill would also be avoided.

However for oxo-degradable plastics to move into mainstream use, farmers would have to be convinced of their effectiveness and environmental safety. In particular farmers would want to know that the Environment Agency was convinced of its safety before considering whether to take up the technology. With these points clarified farmers could reasonably make a choice on whether or not to use these materials based on cost.

Another issue which would affect the use of oxo-degradable plastics is the new legislation of manufacturer responsibility for non-packaging plastics, which would include plastic mulch and tree protectors. There would be a statutory obligation for the manufacturer to collect and dispose of such materials. It would be necessary to clarify how oxo-degradable plastics fit into this new legislation. They would be expected to degrade in-situ, but if removed they may become mixed with conventional plastics and this could have down-stream implication for recycling.

C5.3 National Farmers Union (NFU)

Type of Interview: Telephone

Date: 13th May 2009

Interviewee/contact : Robert Caudwell, NFU Waste Issues Spokesperson

Interviewer/author: Jane Clarke

The main problem with using oxo-degradable plastic films as mulch is that the Environment Agency does not consider ploughing-in any of the remaining plastic as appropriate. Recyclers would not want to accept it, so the undegraded material would have to be removed and disposed of in landfill. The materials are generally more expensive than conventional plastics and the additional costs of going to landfill means that oxo-degradable plastics have not generally been used in the UK, except in trials.

It was commented that degradable plastics that could be ploughed in to the soil would be a useful product to be available to farmers, removing the problems of collection and recycling. However, there would have to be very clear standards of (bio)degradability that could be applied to the materials.

6.16 C6: Plastics and Organics Recyclers

C6.1 Association for Organics Recycling (formerly The Composting Association)

Type of Interview: Telephone

Date: 6th March 2009

Interviewee/contact: Emily Nichols

Interviewer/author: Jane Clarke, Loughborough University

The following summarises the views expressed about the effect of oxo-degradable plastics on composting.

Input materials to composting facilities are mostly garden and green wastes from households, landscaping, farms, fruit and vegetable growing and processing of crops where materials are clearly compostable and there is a low risk of contamination. However, now that Local Authorities are looking at food waste composting in enclosed / in-vessel systems, contamination by non-compostable plastic could become a problem if the local authority is not sufficiently clear about how to recognise and whether to collect 'compostable' plastics for composting. Given the widespread confusion of terms 'biodegradable', 'compostable', 'degradable' and 'oxo-degradable' and 'oxo-biodegradable', householders could mistakenly include oxo-degradable plastics with their food waste, believing them to be 'compostable'. Some Local Authorities are aware of the potential confusion so supply their own kitchen caddy liners, while others specify particular liner products that should be available locally. Some Local Authorities try to persuade the composter to take any 'biodegradable' packaging/plastic wastes. There have been problems with paper and card (when present in relatively large volumes) but the impact of plastics is more difficult to evaluate because there is generally much less of this currently collected with food waste. WRAP is commissioning a consumer focus group evaluation of options for a home compostable certification mark and on-pack label text. It could help to inform householders which plastics can be put in their own home composting bins or included with food waste collected on behalf of the Local Authority.

In composting material, if there are significant amounts of plastics present during composting this could adversely affect air circulation. This could lead to anaerobic air pockets developing, which generates malodours and make odour management more difficult.

Windblown litter must not escape from composting facilities. If there is an outdoor phase in the composting process this could be a problem if plastics are present. Barriers or nets can be used but this adds to the cost and they are not necessarily effective.

Fragmentation of the plastic can make separation difficult if an industrial screen is used since the dimensions and density of the plastic particles are similar to those of the other compost particles. Further processing at additional cost may achieve adequate removal but the costs and efficacy have not been evaluated or quantified.

For compost to be treated as a product, rather than a waste material, it must comply with the PAS100 standard and the Compost Quality Protocol. The latter represents further industry self-regulation.

In the PAS100 standard (and Compost Quality Protocol) there are various requirements that must be met. One of these is that the only input materials that are accepted are those that pass one or more of the compostability standards, i.e. EN 13432, EN 14995, DIN V 54900 or ASTM D6400. Oxo-degradable plastics do not pass any of these standards and so are excluded from composting.

As a provision for the control of incidental contamination by plastic, the PAS 100 standard does allow for the presence of a very limited amount of contamination. There are specified limits to contaminants above 2 mm in size. Plastic particles greater than 2 mm in size must not exceed 0.25 % by weight of the compost. In practice, values are generally much lower than this as compost buyers and users are intolerant of physical contaminants in composts. PAS 100, includes a further requirement that the compost is “fit for purpose”. For example, the customer may still reject the compost on basis of appearance, even if the total plastic is less than 0.25 % (or possibly more than this but in visible fragments less than 2 mm in size). PAS 100 places responsibility on the compost producer to supply compost that is ‘fit for purpose’.

If not compliant with PAS100 (and the Compost Quality Protocol in England or Wales), compost is legally assumed to be waste until it has been used and such use has not resulted in pollution of the environment. The composter has to obtain permission from the regulator to spread the particular compost in a particular area, at particular time, taking account of the land use. The regulator is the Environment Agency in England and Wales, Scottish Environmental Protection Agency (SEPA) in Scotland and Department of Agricultural and Rural Development (DARD) in Northern Ireland. The regulator may refuse if residual plastic is present in the compost.

The European Standard for compostability of materials, EN 13432 (and the technically equivalent standards referred to above), does not exclude any specific plastics. To date, oxo-degradable plastics have not passed the ‘biodegradability’ test in the EN 13432 standard.

Proponents of oxo-degradable plastics want to modify the standards to give a robust framework for testing and reporting (bio)degradation. However, there are already standards available in the USA which could be used and it is not clear why a new standard should be developed.

Previous drafts of a prospective new British Standard for oxo-degradable plastics have made numerous references to composting in the expectation that the composting industry will

accept such plastics. However, the view expressed was that the research showed extremely variable results and the Association for Organics Recycling requested that all references to compostability of oxo-degradable plastics to be removed.

Misinterpretation of EN 13432 has occurred because it includes one note that has been quoted without reference to this standard's other important provisions. The quoted note states that *'It is important to recognise that it is not necessary that biodegradation of packaging material or packaging be fully completed by the end of biological treatment in technical plants but that it can subsequently be completed during the use of the compost produced'*. This has led to the proponents of oxo-degradable plastics saying that this should apply to oxo-degradable plastics. However, EN 13432 strives to limit the risk to compost quality by including another note states that *'Special attention should be given to the visual aspects of compost. Visual contamination of compost, as evidenced by reduction of aesthetic acceptability, should not be significantly increased by any post composting residues of the packaging material introduced'*. Clearly there is an interpretation problem and it should be looked at if the standard is reviewed.

The proponents of oxo-degradable plastics have attempted to justify the use of oxo-degradable plastics by claiming that return of carbon to the soil is good, including return via partially degraded plastic fragments. However, the Association for Organics Recycling does not consider this is right in terms of littering in the environment, and has potential to greatly harm the saleability and usability of composts if oxy-biodegradable plastics are pushed towards the composting route for waste recovery.

C6.2 Composting Company A

Type of Interview: e-mail communication

Date: 2nd March 2009

Interviewer/author: Jane Clarke, Loughborough University

The following information was provided in an e-mailed response to an enquiry about the effect of oxo-degradable plastics on composting.

Composting Company A has carried out a rough (non-controlled) trial on so-called 'bio-degradable' or 'compostable' plastic bags. Ten to twenty 'compostable' plastic bags were put in a (non-degradable) plastic onion sack, placed amongst the green waste in an ABPR (Animal By-Products Regulation) compliant in-vessel composting system (mixed food and garden waste from council kerbside collections). After the composting process (2 weeks in vessel achieving at least 60C for at least 2 days and then 6 weeks in windrows being turned) the onion bags were retrieved during the compost screening process, and their contents examined. In general, the cheaper the 'compostable' bags the less well they broke down. The most expensive bags tended to degrade substantially, while the cheap versions hardly composted at all (most looked 'as good as new').

Composting Company A has no policy on the inclusion of degradable plastics, taking whatever green waste local authorities provide, unless it is heavily contaminated. Composting Company A has worked with the local authorities for years on campaigns to raise awareness about not putting food waste (in particular) in plastic bags in the green bin for the compost collection. The local authorities have a policy of asking their collection crews to check green bins before emptying and reject any contaminated with plastic bags. This policy and the awareness campaigns have not been very successful. The green waste received from local authorities is still contaminated with plastic bags and around 30% of the compost has to be rejected after screen due to contamination with plastic. At present Composting Company A and the local authorities are not saying that residents can use 'compostable' plastic bags, because of their potentially poor compostability and because of

the risk of confusion with ordinary plastic bags by both the consumer and the collection crews.

It is considered that the best policy is to allow no plastic bags of any sort in the green waste. Reference is made to an article which concludes that increasing use of 'compostable' bags will lead to higher contamination levels and more green waste ending up in landfill (Dr. Stephen Wise, 'Degradable does not mean compostable', 'Resource Management and Recovery' issue 160, 6th Feb. 09).

C6.3 Recycling company A

Type of Interview: telephone

Date: 13th May 2009

Interviewer/author: Jane Clarke, Loughborough University

Recycling company A manufactures polyethylene products, including those for agricultural applications. Oxo-degradable plastics are among their products. Recycling company A also carries out substantial recycling of polyethylene.

In agricultural use, it had been found that there were problems associated with predicting the time to break down of the plastic. The importance of controlling this was emphasised, if degradation was either too later or too early there would be problems. It was commented that biopolymers generally performed better but were not generally used because of their high cost.

From the point of view of recycling it was admitted that, strictly speaking they can be called recyclable since they can be melted down and re-used. However, it was considered that their lack of stability, due to the presence of remaining pro-degradant means that their recycling is problematic. A particular problem arises as many recycled plastics are used in building films where they need to function long-term. When this point had been raised with an additive producer it was suggested that recycling more stabilisers could be added to compensate. This was not considered by Recycling Company A to be a reasonable solution and it was added that, if used in agricultural plastics the oxo-degradable plastics would not be allowed to be taken in for recycling.

Recycling company A was not against the use of oxo-degradable plastics in principle, but commented that it would be a matter of using them in the right application. It was thought that it would be more acceptable to use biopolymers which are compostable, to allow diversion from landfill to composting.

As an anti-litter strategy the use of oxo-degradable plastics was thought to be reasonable. However it was considered that where there is a clear route to recycling it is better to recycle than to follow the degradable route.

C6.4 RECOUP

Type of Interview: email communication

Date: 12th May 2009

Interviewee/contact: Ben Layton

Interviewer/author: Stuart Patrick

RECOUP is a national charity developing plastics recycling in the UK, promoting best practices and providing educational and training tools

Some films such as carrier bags can be recycled but into relatively low value applications. Therefore a limited amount of household films are currently collected, baled and sold to reprocessors, but this is often at a negative value. The plastic film also causes technical issues with sorting equipment in materials reclamation facilities. The Recoup guide currently specifies that film should not be collected for recycling. A key area of recent WRAP research has proven that mixed domestic film recycling can be achieved under trial conditions, although the increasing levels of bioplastics present in carrier bags and other films may present issues generally for the commercialisation of recycling petrochemical based plastics. The challenge is now to enable collection, handling and effective separation of film from other recyclables within acceptable cost boundaries given the relatively low output value.

A domestic mixed plastics packaging recycling guide was also provided.

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