Study to provide information supplementing the study on the impact of the use of "oxo-degradable" plastic on the environment"

Final report

April 2017

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The Impact of the Use of "Oxo-degradable" Plastic on the Environment

Final Report for the European Commission DG Environment. Project conducted under Framework Contract No ENV.A.2/FRA/2015/0008 and 07.0201/2016/748104/ETU/ENV.B.3.

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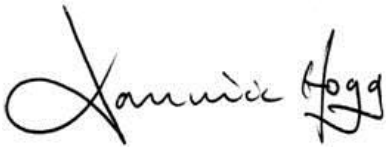

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Executive Summary

E.1.0 Overview and Summarised Conclusions

Oxo-degradable or oxo-*bio*degradable plastics are conventional plastics, such as High Density Polyethylene (HDPE), commonly used in carrier bags, which also include additives which are designed to promote the oxidation of the material to the point where it embrittles and fragments. This may then be followed by biodegradation by bacteria and fungi at varying rates depending upon the environment. It has been debated for some time whether or not these additives perform in the way in which their manufacturers claim they will, whether they cause harm to the environment, and whether they effectively make plastics recycling more problematic.

In November 2014, Members of the European Parliament proposed an outright ban on "oxo-degradable" plastics within the EU. Although this measure was blocked, an amendment to the Packaging and Packaging Waste Directive, adopted in May 2015, commits the Commission to examine the impact of the use of oxo-degradable plastic on the environment;

> *"By 27 May 2017, the Commission shall present a report to the European Parliament and to the Council, examining the impact of the use of oxo-degradable plastic carrier bags on the environment and present a legislative proposal, if appropriate."*[1]

This study has been undertaken in response to that request and compiles the requisite information regarding environmental impacts of this material, to the extent that such information is available, in order to form an opinion on any appropriate actions to be taken. The report presented here draws on the available scientific literature in order to investigate the claims from the industry with regard to biodegradation in different environments, and compatibility with current recycling processes. Input from key stakeholders—including the industry itself—has been used during the review to understand the impacts of the use of these materials.

Throughout this study, the material is referred to as **Pro-oxidant Additive Containing (PAC) Plastic** as a means of describing the material's physical make up, and without implying any presumption as to how it will behave in different environments.

[1] Directive (EU) 2015/720 amending DIRECTIVE 94/62/EC on packaging and packaging waste

E.1.1 Issues Related to Biodegradation

The following are the key findings of this study regarding whether or not PAC plastic biodegrades in different environments.

Composting and Aerobic Digestion

The evidence suggests that PAC plastic is not suitable for any form of composting or Anaerobic Digestion process and will not meet current standards for packaging recoverable through composting in the EU (EN 13432). PAC plastics are designed to degrade in much slower timeframes than are required for industrial composting. There is, therefore, a risk that fragmented plastics could be applied to land. In most countries that have compost standards in place, the output is strictly controlled, and the presence of plastic fragments would invariably lead to a failure to meet these standards. It should be recognised that the majority of PAC plastics manufacturers do not claim that their products are suitable for composting.

Open Environment

The review of evidence undertaken for this report suggests that whilst PAC plastic *can* biodegrade under certain circumstances, there is still doubt as to whether they *do so* fully or within reasonable time periods in practice (and acknowledging the impracticality of defining what a 'reasonable' time period might be). One finding that is clear is that PAC plastic is prohibited from biodegradation if it is not first exposed to UV radiation (and, to a certain extent, heat). This breaks down the anti-oxidants and accelerates the oxidation process that is triggered by the pro-oxidant additives. This first abiotic stage of degradation prepares the PAC plastic for biodegradation by reducing the molecular weight of areas on the plastic surface to the point where it can be consumed by biological organisms, kick-starting the biotic degradation phase. If the circumstances for this to take place are absent (e.g. if UV exposure is only fleeting), biodegradation will either not take place (it will behave as a conventional plastic) or will be slowed significantly. This is the same for all environments.

Extrapolations from a laboratory study on a particular LDPE film engineered with a short service life suggest that almost complete degradation in soil can be achieved within two years (following perhaps one year of abiotic degradation while the material is in use). With the results of the laboratory study showing over 91% conversion to CO_2, the author contends that the *"risk of plastic fragments remaining in soil indefinitely is very low."* Nowhere is such a claim for complete bio-assimilation proven in practice though.

Other studies have shown significantly reduced biodegradation, suggesting that anything less than ideal conditions will, at very least, extend the timeframe for biodegradation. Furthermore, different products should be expected to behave differently. One major issue for PAC plastic is the trade-off between the intended service life period, and the period that may be needed for degradation in an open environment. Although it can be believed that biodegradation can be facilitated by careful engineering of the chemical package in PAC plastic, evidence is not available to definitively conclude that this will happen in real world situations with PAC plastic products being placed on the market.

Landfill

The degradation that occurs in landfill is primarily confined to the initial aerobic stage in the higher levels of the landfill. In the absence of oxygen (under anaerobic conditions of landfill operations), the PAC plastic is thought not to biodegrade. This makes PAC plastic marginally worse than conventional plastic from a GHG point of view as it may lead to emissions of fossil CO_2 during the period where biodegradation takes place (if it does in practice to any meaningful degree).

Marine Environment

There is currently insufficient evidence to provide assurance that PAC plastic will biodegrade in the marine environment. Very few tests have been conducted, and there are currently no standards that can be met which will allow a certification. Biodegradation is expected to be much slower in water compared to land based open environments. Evidence is not available to properly understand the fate of PAC plastic in marine environments, and thus there remains a risk that plastic fragments may remain either indefinitely, or for long enough to cause significant environmental damage.

E.1.2 Issues Related to Littering

Directly related to the issues of biodegradation are those of littering and how the PAC plastic will behave if it is littered, and thus, what impacts might be expected.

Toxic Effects

The potential toxic effects on soils of any residual additives have been identified as a concern by some commentators. Whilst it has not been conclusively proven that there are no negative effects, it does appear that the PAC plastics industry can create products that have minimal toxic impact on flora and fauna. This does not mean that all products on the market avoid negative toxic effects, as there is no regulatory control currently exercised in this regard. It is at least encouraging that almost all existing test standards for PAC plastic specify some form of toxicity test using established methods (such as germination and earthworm survival tests). However, problems remain that (a) accreditation is not mandatory for products on the EU market, (b) some of the standards do not have pass/fail criteria for the toxicological test results, and (c) there remains uncertainty surrounding real world toxicological impacts.

Increase in Littering

There is a suggestion, on the basis of the evidence which is available, that indicates a greater tendency for littering to occur if the user believes that the substance is ‘biodegradable’. Although there is no noticeable physical difference between PAC plastic (until it starts to fragment) and conventional plastic, specific markings can be placed on products at the point of manufacture to differentiate a PAC plastic product. It is also possible–indeed it seems quite likely–that there would be some form of marketing extolling the claimed benefits of PAC plastic products in this regard. Consequently, it may be that littering of PAC products is more likely because of claims regarding their biodegradability. Nevertheless, rather than speculation, objective behavioural research is required to move this topic forward in a constructive manner.

Marine Litter

As indicated above, there is no conclusive proof of PAC plastic biodegradation in the marine environment. It is the least aggressive of all the environments investigated in this report, but arguably, it is also the environment where the most damage could be done, and with the least chance of subsequently recovering the plastic.

With PAC plastic being more likely to fragment than conventional plastic, to the extent that this occurs, it is less likely to be recovered during litter clean-up exercises, and will also likely be more easily mobilised. These factors can be reasoned to increase the chance of being transported into the marine environment. However, should full biodegradation on land occur, this would reduce the quantity that may otherwise transfer to the marine environment. It is not possible to conclude whether PAC plastic would increase or decrease absolute quantities of plastic in marine environments. Nonetheless, it seems likely that the fragmentation behaviour of PAC plastics will exacerbate issues related to microplastics.

Working under the assumption that PAC plastic in marine environments will be more fragmented, the effect may be to reduce the impacts on wildlife in some respects (such as entanglement), but to increase the impacts in others (such as physical ingestion of microplastics). The PAC plastic is more likely to fragment quicker so the impacts associated with microplastics are concentrated within a shorter period of time—this could ultimately be worse than spreading out the impacts over a longer period of time due to an increase in the proportion of individuals, species and habitats affected, as well as the burden of impacts for an individual of a species. Although we are not able to provide conclusive judgement on marine issues, concerns remain that PAC plastics do not eliminate impacts, and also that impacts may be increased in certain important impact categories.

E.1.3 Issues Related to Recycling

On issues relating to recycling of PAC plastics, the following key conclusions are drawn.

Identifying PAC Plastic

The evidence available does not support the suggestion that PAC plastic can be identified and sorted separately by reprocessors with the technology that is currently available. Furthermore, manual sorting would be time-consuming and is unlikely to be economically viable. In the absence of market controls within any individual country, recycling of PAC plastic must, therefore, be considered in the context of a mixture with conventional plastic.

Quality Issues

There are significant concerns within the recycling industry that PAC plastic negatively affects the quality of recycled plastics. Evidence suggests that the impacts of prodegradant additives on recyclates can under certain circumstances be avoided with the inclusion of stabilisers. The appropriate quantity and chemistry of stabiliser would depend on the concentration and nature of the prodegradants in the feedstock. This presents significant issues, as the concentration of PAC plastic in recyclate in real world

situations where the market is not controlled is unknown, and therefore it is difficult to know the correct dosing. Furthermore, evidence suggests that oxidised PAC plastic can significantly impair the physical qualities and service life of the recycled product. The fact that it is impossible to fully control the level of aging experienced by PAC plastics during the product use phase, prior to products becoming waste and entering recycling processes, presents a major issue.

Recyclate made from mixtures containing unknown PAC plastic should not be used for long-life products, due to the lack of evidence surrounding the long-term impact in secondary products. The existence of PAC plastic and the global nature of secondary materials markets does, therefore, present risks of using recovered plastic in such applications. The uncertainty of whether recyclate may–or may not–contain PAC plastic, and the degree of oxidation likely to have occurred prior to recovery, therefore results in limits on the end-use for the recyclate.

For shorter-life products, it may be possible to create a recyclate, which has no reduced properties over the short-term life of a particular product. However, most of the evidence suggests that the concentration of PAC plastic in the feedstock resin may be important – though evidence is not sufficient to suggest what limits should be followed. It must also not be ignored that any oxidation and degradation of PAC plastic that occurs prior to recycling will impair the recyclate.

Marketability of Recyclates

Opinions and anecdotal evidence provided by the plastics recycling industry indicate there is significant risk associated with PAC plastic due to the way in which it is perceived by reprocessors. The inclusion of PAC plastic has a negative effect on the marketability of plastic films sent for recycling. The industry is keen to eliminate PAC so as to minimise any effect on prices related to the quality and marketability of secondary materials.

E.1.4 Summary

This report is split into 13 distinct hypotheses, each of which reflect either a claim from the PAC plastics industry or a commonly held belief about the material. The hypotheses are addressed, in turn, and the evidence is gathered and analysed to ascertain whether the hypotheses can be supported or refuted. The summary of this exercise is shown in Table E - 1 (with a green to red colour coding indicating whether each hypothesis is upheld or not).

Table E - 1: Summary Findings

Hypotheses	Hypothesis supported by the evidence?
Issues of Biodegradability	
Hypothesis 1: In open environments, pro-oxidant additives will accelerate the fragmentation of traditional polymers.	**Supported**
Hypothesis 2: PAC plastics should not be considered compostable.	**Supported**

Hypothesis 3: In open environments, PAC plastics biodegrade following their fragmentation.	**Partially Supported**
Hypothesis 4: PAC plastics do not biodegrade in landfill.	**Supported**
Hypothesis 5: PAC plastics biodegrade in marine environments .	**Inconclusive**
Issues of Littering	
Hypothesis 6: In soil, fragmented and potentially partially degraded plastics and their additives pose limited negative effects to soil quality or ecosystems.	**Inconclusive**
Hypothesis 7: The use of PAC plastic does not instil or promote a throwaway attitude.	**Inconclusive**
Hypothesis 8: PAC plastic is a possible solution to reduce the problems of plastic marine litter compared with conventional plastic.	**Inconclusive**
Issues Relating to Recycling Processes	
Hypothesis 9: PAC plastics can be identified and separated in collection systems.	**Refuted**
Hypothesis 10: PAC plastics can be identified and separated within recycling processes.	**Refuted**
Hypothesis 11: The quality of conventional plastics recyclate is not negatively affected by PAC plastic added to the feedstock.	**Refuted**
Hypothesis 12: The presence of PAC plastics in recyclate does not affect recyclate prices or marketability.	**Refuted**
Hypothesis 13: The presence of PAC plastics in recyclate does not affect the ability of manufacturers to guarantee specific business requirements relating to physical properties (such as tensile strength etc.).	**Market dependent**

E.2.0 Recommendations

The debate around the biodegradability of PAC plastic is not finalised, but should move forward from the assertion that PAC plastics merely fragment, towards confirming whether the timeframes observed for total biodegradation are acceptable from an environmental point of view and whether this is likely to take place in natural environments. The variety of formulations—most of which are proprietary and confidential—and the lack of regulation of them means that there are no guarantees that all PAC plastic will perform appropriately in the markets in which they are sold, and in environments they may end up.

No suitable certifications are available currently that allow a PAC plastic supplier to claim that biodegradation will happen in a certain environment to a particular set of requirements. Certifications from France and the UAE are not without shortcomings, and neither should be adopted as best practice by the EU. For PAC plastic to remain on the market, work to develop a (set of) European standard(s) should be a matter of priority.

One of the biggest issues to be confronted by both policy makers and the PAC plastics industry when deciding on limits and controls is that there are no unified standards. We

have observed throughout this research that the PAC plastics industry consists of different manufacturers and stakeholders, each of which claims to have developed the definitive method for assessing biodegradability: indeed, new methods appear to be surfacing all the time. This makes it less than straightforward to garner a rational body of evidence on the matter—as results from differing tests are incomparable—and to define a suitable approach through which one can be sure that the PAC plastics industry, as a whole, produces products that are not environmentally harmful.

In the meantime the PAC plastics industry should be prevented from selling their products into markets that have been conclusively proved to be unsuitable—primarily composting and AD markets. There is also no clear evidence to support the contention that PAC plastic is a solution to the problem of plastic in the marine environment: it is suggested that no form of communication should be permitted that uses this as selling point, especially for single use items (the sort of products which PAC plastic is primarily aimed at).

It would go some way to alleviate fears of toxic effects if all PAC plastic products in the market were required to pass toxicity tests. As the PAC plastics manufacturers specifically state that their products are designed to help deal with the effects of littering it is incumbent upon them to demonstrate that each product they sell does not have a negative toxic effect on the environment that it may be littered into. Such tests should be included as part of any European standard.

The issue of littering behaviour is something not confined to PAC plastic but applicable to all products that claim to be biodegradable or compostable—terms which are often synonymous in the mind of the consumer. California recognised this issue, and in 2011, regulated the use of these terms to help consumers make informed decisions without 'greenwash', and to target littering.[2] Specifically:

> *"Environmental marketing claims, whether explicit or implied, must be substantiated by competent and reliable scientific evidence and meet specified standards to prevent misleading consumers about the environmental impact of degradable plastic products, including bags, food service ware, and packaging."*

This has resulted in court action on multiple occasions. The legislation also encourages manufacturers to work towards the production of appropriate standards that allow sound scientific tests to be performed to support any claim. Similar standardised regulation and alignment of nomenclature would also be beneficial to the EU and create a level playing field for manufacturers of products that are genuinely biodegradable in the relevant environments. It would also incentivise the PAC plastics industry towards aligning their efforts towards creating effective standards.

[2] California Senate Bill No. 567 http://www.leginfo.ca.gov/pub/11-12/bill/sen/sb_0551-0600/sb_567_bill_20111008_chaptered.pdf

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Glossary

The following is a list of terminology and acronyms which are used in this report. Some are directly from CEN standards whilst others are specific to this study.

Abiotic degradation

Degradation from physical mechanisms as opposed to attack from biological organisms.

Anaerobic Digestion (AD)

An industrial process often used for sewage and food wastes, involving the biodegradation of material without oxygen present.

Biodegradable Plastic

Plastic which degrades as a result only of a biotic process in a relatively short time-frame (as defined and tested, in Europe, according to standard EN 13432). These plastics are not covered by the scope of this Report, and are only mentioned as appropriate.

Biodegradation

Degradation of a polymeric item as a result of cell mediated phenomena. (CEN TR 15351)

Biotic degradation

Degradation via attack from biological organisms.

Conventional Plastic

For the purposes of this report this refers to plastic which does not contain any pro-oxidant additives or is otherwise designed to biodegrade. It is often used as the control in comparative biodegradation tests.

Degradation

Change in initial properties as a result of chemical cleavage of the macromolecules forming a polymeric item, regardless of the mechanism of chain cleavage. (CEN TR 15351)

Microplastics

Plastics that have been fragmented or manufactured to a size smaller than 5mm.

Oxidation

Process promoted thermally or by ultraviolet (UV) radiation or both in the presence of oxygen. (CEN TR 15351)

Oxo-biodegradation

Degradation resulting from oxidative and cell mediated phenomena either simultaneously or successively. (CEN TR 15351)

Oxo-degradation

Degradation resulting from oxidative cleavage of macromolecules. (CEN TR 15351)

Plastic(s)

Material that contains as an essential ingredient one or more organic polymeric substances of large molecular weight, is solid in its finished state, and, at some stage in its manufacture or processing into finished articles, can be shaped by flow. (ASTM D883)

Pro-oxidant Containing (PAC) Plastic

Plastic material that contains additives that may accelerate the oxidation of the material under certain conditions. This may then promote follow-on biodegradation.

1.0 Overview and Methodology

1.1 Background / History

The high molecular weight and hydrophobic nature of conventional plastic lends the material high resistance to biological attack. However, for situations where biodegradation is a desirable attribute, the second half of the 20th century saw attempts to develop the first plastics deliberately engineered to age upon the application of heat and light. These plastics included the deliberate incorporation of pro-oxidants or prodegradants (often polyunsaturated compounds, transition metal ions or metal complexes such as dithiocarbamates) intended to encourage the in-situ generation of carbonyl groups[3], or the incorporation within the polymer of carbonyl groups themselves. Such functional groups act as initiators of thermal and photo-oxidation of the hydrocarbon polymer chains. Repeated photo- or thermal-molecular cleavage leads to lower molecular weight polymer chains, whereupon the material becomes more susceptible to biological degradation.[4]

Within the current century, the focus has shifted to materials marketed as "oxo-degradable" or "oxo-biodegradable" plastics. These are plastics which contain additives intended to initiate degradation as well as stabilisers (anti-oxidants) intended to delay this effect until it is desired to occur if, and when, an item is discarded in the natural environment. These plastics are intended to go through both abiotic degradation (for instance embrittlement and mechanical damage) and biotic degradation processes (i.e. biodegradation), accelerated by light and/or heat, until they are, ultimately, fully bio-assimilated.

The 2013 Commission "Green Paper on a European Strategy on Plastic Waste in the Environment"[5] identified various problems associated with degradable plastics, including the risk of contributing to marine microplastics. The paper also asked whether interventions are needed to safeguard recycling processes. An analysis[6] of a public consultation—mainly consisting of trade associations and public administrations—based upon the green paper found that of 119 respondents, 53% suggested oxo-degradable plastic should be prohibited and 33% suggested it should not be promoted with 1% suggesting it should be promoted. The main concerns raised were that oxo-degradable plastic might hinder recycling; it has a negative environmental impact; and it can create a littering problem.

In November 2014, Members of the European Parliament proposed an outright ban on oxo-degradable plastics within the EU. Although this measure was blocked, an amendment to the Packaging and Packaging Waste Directive, adopted in May 2015, commits the

[3] A carbonyl group is a functional group within the molecular structure consisting of a carbon atom double-bonded to an oxygen atom.

[4] Chiellini, E., Corti, A., and Swift, G. (2003) Biodegradation of Thermally-oxidized, Fragmented Low-density Polyethylenes, *Polymer Degradation and Stability*, Vol.81, No.2, pp.341–351

[5] European Commission (2013) *GREEN PAPER: On a European Strategy on Plastic Waste in the Environment*, 2013

[6] BIO Intelligence Service (2013) *Analysis of the public consultation on the green paper 'European Strategy on Plastic Waste in the Environment'*, Report for EUROPEAN COMMISSION DG Env, November 2013

Commission to examine the impact of the use of "oxo-degradable plastic"[7] on the environment:

> *"By 27 May 2017, the Commission shall present a report to the European Parliament and to the Council, examining the impact of the use of oxo-degradable plastic carrier bags on the environment and present a legislative proposal, if appropriate."*[8]

This study takes place in response to that request.

The study compiles information regarding the environmental impacts of oxo-degradable bags, to the extent that such information is available. It draws on the available scientific literature and input from key stakeholders contacted during the review to understand the impacts of the use of these materials. The information is used as a basis for proposing actions that could be taken.

1.2 Methodology

The terms for the study were defined by the European Commission to appraise the existing literature and information from stakeholders to assess the biodegradability of oxo-degradable plastics in various environments, to assess the impact upon recycling, and to assess the environmental impacts in relation to littering. The approach taken within this report, considered and approved by the Commission, is to formulate the key environmental issues relating to the use of oxo-degradable plastic, or the factors underpinning them, within Section 3.4.5, as a series of hypotheses. The science and available literature are then explored and debated to test and (if possible) come to a conclusion as to whether each hypothesis can be supported, or whether problems or uncertainty give specific cause for concern.

As part of this, relevant stakeholders and technical experts have been contacted and interviewed in subject areas that required more in-depth analysis. The focus is on technical and scientific evidence building. In some cases the evidence is still inconclusive— recommendations are then provided for how this should be tackled.

1.3 Terminology and Definitions

There are many terms for plastics which include compounds that promote degradation. The oxo-biodegradable industry favour oxo-*bio*degradable as they assert that the plastic is biodegradable, whilst others refer to the products as oxo-*degradable*. Other terms that are used are plastic with a 'prodegradant',[9] or 'pro-oxidant'[10] additive.

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[7] Defined in the Directive as "plastic carrier bags made of plastic materials that include additives which catalyse the fragmentation of the plastic material into micro-fragments."

[8] Directive (EU) 2015/720 amending DIRECTIVE 94/62/EC on packaging and packaging waste

[9] Edwards, D.C. (2011) *Life Cycle Assessment of Supermarket Carrier Bags*, Report for Environment Agency, February 2011

[10] Husarova, L., Machovsky, M., Gerych, P., Houser, J., and Koutny, M. (2010) Aerobic biodegradation of calcium carbonate filled polyethylene film containing pro-oxidant additives, *Polymer Degradation and Stability*, Vol.95, No.9, pp.1794–1799

Oxo-biodegradation is defined by CEN/TR 15351:2006[11] as

> *"degradation resulting from oxidative and cell-mediated phenomena, either simultaneously or successively"*

This definition is often referred to in other national and international test standards. Some of these standards (as discussed further in Section 3.0) also provide pass/fail criteria, so that a failure of these tests would mean that it would be inappropriate to refer to the test sample as oxo-biodegradable in the context where the standard is applied. In this regard, the inclusion of a pro-oxidant additive will not automatically make a *'non-degradable'* plastic *'degradable'*.

In the interests of developing neutral terminology, this report refers to the plastic in terms of its physical make up, rather than making reference to how it will behave in different disposal environments. We refer to the products as:

Pro-oxidant Additive Containing (PAC) Plastics

The industry that produces the pro-oxidant additive for use in plastics will, likewise, be referred to as the PAC plastics industry.

At the outset it is also important to discuss and make clear the terminology that will be used throughout the report especially with regard to biodegradability. The term biodegradable is essentially meaningless in isolation, and must be put in the context of where the biodegradation is assumed to occur; whether in the soil, in commercial or home composting, anaerobic digestion, in the rivers and oceans, or in the open environment (i.e. littered). Each environment has its own temperature, UV level, moisture level and bacterial and fungal colonies which govern the likelihood and speed of biodegradation of different materials. This study examines each of the key environments, in turn, for evidence of the extent to which PAC plastics will degrade both biotically and abiotically—i.e. with or without attack from biological organisms.

Biodegradable and compostable are also terms that are often used interchangeably. It is true to say that a compostable plastic is biodegradable [under the definition of a composting standard], but a biodegradable plastic is not always compostable. As already described, composting—whether commercial or at home—is just one environment within which a material may biodegrade, and therefore, the two terms should not be erroneously linked.

It is also important to dispel the popular misconception that the raw material used for a plastic, whether fossil derived or bio-based, directly determines its biodegradability. For example, some plastics are made almost entirely from bio-based and, potentially, renewable resources, but depending on their make-up, they can be designed to biodegrade[12] under certain conditions or to behave as a conventional plastic.[13] Similarly,

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[11] PD CEN/TR 15351: Plastics. Guide for vocabulary in the field of degradable and biodegradable polymers and plastic items

[12] NatureWorks (2016) *Turning Greenhouse Gases into Ingeo Biopolymer*, accessed 6 January 2016, http://www.natureworksllc.com/The-Ingeo-Journey/Raw-Materials

[13] Braskem (2016) *I'm Green™ Polyethylene*, accessed 1 June 2016, http://www.braskem.com/site.aspx/Im-greenTM-Polyethylene

there are also fossil-derived plastics available which are designed to biodegrade.[14] Therefore, not all bio-based plastics are biodegradable, and not all biodegradable plastics are bio-based.

[14] BASF (2016) *Biodegradable and Compostable Packaging solutions with ecoflex®*, accessed 1 June 2016, http://product-finder.basf.com/group/corporate/product-finder/en/brand/ECOFLEX

2.0 The Oxo-Biodegradable Industry

There are currently two trade bodies that represent the PAC plastics industry on a global level – the Oxo-Biodegradable Plastics Association (OPA) and the Oxo-Biodegradable Plastics Federation (OBPF).

The OPA[15] is a UK based organisation with 1,602 members, including manufacturers, distributors, importers and commercial end users throughout the world. A prominent member of the OPA is Symphony Environmental Technologies PLC[16] who are also UK based. Symphony (via one of its two subsidiary organisations) manufactures various additives and masterbatches for plastic products (not the plastic itself). They are one of the market leaders in this field and are well represented in all major national and international discussions, as well as funding research into the subject. The OPA and Symphony have both been consulted, and have contributed information to this study.

In February 2016, the majority of the other industry market leaders formed the OBPF. Its membership includes;

- **Add-X** producers of **Addiflex**[17] (Sweden)
- **EPI Environmental** producers of **TDPA**[18](Canada)
- **Well Plastics** producers of **Reverte**[19] (UK)
- **Willow Ridge** Plastics producers of **WRP**[20] (USA)

Each of these produces its own additives under the brands specified and many of them feature throughout this report as the funders of research into the field of PAC plastic. The OBPF was consulted, and contributed information for this study on behalf of its members.

Further information on the PAC plastics industry has been gathered as a discrete market assessment study, and this is presented in Appendix A.1.0.

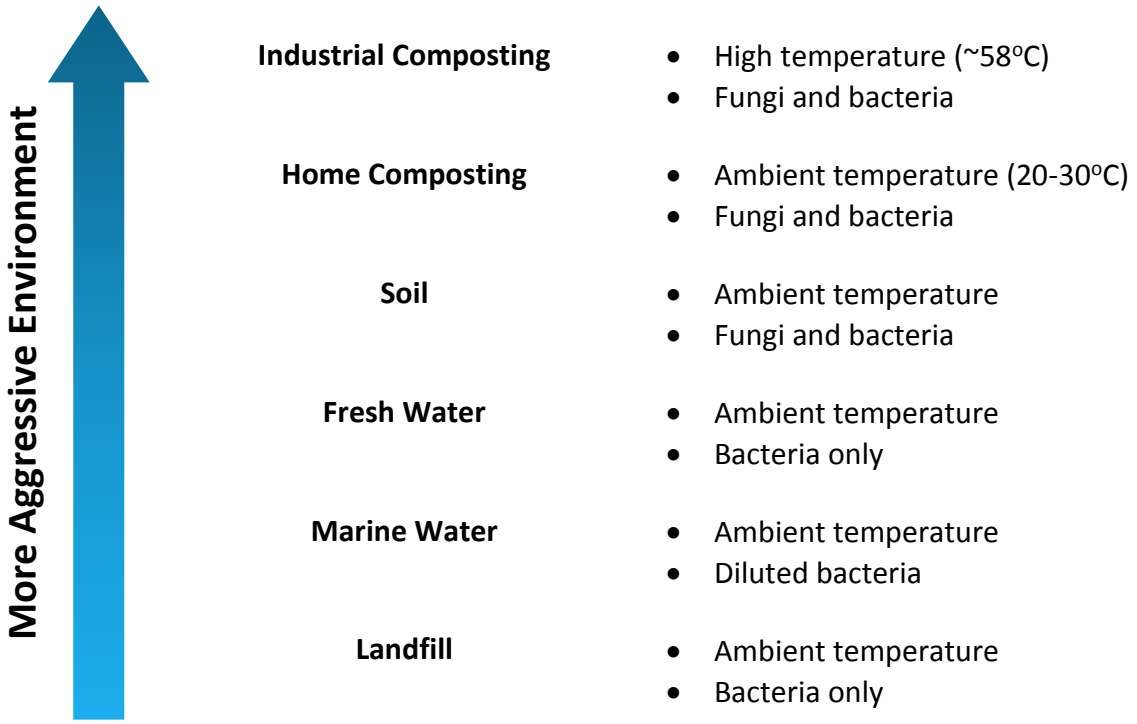
[15] http://www.biodeg.org/
[16] http://www.symphonyenvironmental.com/
[17] http://www.add-xbiotech.com/products.aspx
[18] http://www.epi-global.com/en/products.php
[19] http://wellsplastics.com/Products/biodegradables/
[20] http://www.willowridgeplastics.com/contact/oxo-biodegradable/

3.0 National and International Standards

The following is an overview of the most relevant standards for biodegradation in compost, marine and freshwater, and soil. As highlighted already, each environment has its own specific set of conditions: it cannot, therefore, be assumed that if a plastic biodegrades in one environment, it will do so in the others. Different test methods and standards for biodegradation are required for each environment. It is also important to recognise that, in general, there is a hierarchy of how aggressive these environments are which gives an indication of whether a material may biodegrade. A rudimentary basis hierarchy is found in Figure 1: which presents the supposition that if a material does not, for example, compost, then it is unlikely to biodegrade in soil or water.

Importantly, industrial composting is the only controlled biodegradation environment. All other environments have a number of external factors (heat, light, moisture etc.) that will have a significant effect on the level of biodegradation. This means that real world conditions are often hard to replicate in a laboratory. As the standards that are discussed in the following sections demonstrate, their basis in laboratory testing means that achieving a standard or a certification reflects the current state of development of testing methods, and should not necessarily be considered as definitive evidence of what happens in real-world situations. Standards for biodegradation in freshwater and marine environments are particularly difficult to develop in this regard. The key national and international standards (as well as private accreditations where no public ones exist) that are used for certification purposes are also summarised for comparison in Table 1 at the end of this section.

Figure 1: Ranking of the Aggressiveness of Biodegradation Environments



3.1 Composting Standards

The standard that is most often referred to is European Standard 13432, which is wide in scope as it covers all packaging:

> *Packaging - Requirements for packaging recoverable through composting and biodegradation - Test scheme and evaluation criteria for the final acceptance of packaging*

This standard works alongside EN 14995 which is aimed at non packaging *plastics*, whereas EN 13432 is aimed at *all materials* designed for packaging use. They both have the same criteria, but differ in scope. If a plastic product meets either standard it is deemed an acceptable input to commercial composting systems—but not home composting.

Two biodegradation requirements are specified in this standard depending on whether an aerobic (composting) or an anaerobic (anaerobic digestion (AD)) process is used. The minimum thresholds are 90% biodegradation in 6 months for aerobic composting, and 60% biodegradation in 2 months for AD. The lower biodegradation level and shorter time period for AD is due to the expectation that the process is generally shorter, and that a further composting stage is often used. The standard recommends that testing should be undertaken using the test method from ISO 14855, which requires the measurement of CO_2 emitted from the test sample as an indicator of biodegradation. The test sample must also be tested to make sure it has fragmented sufficiently, and that the resulting compost is not toxic to plants.

The composting process is well understood and can be replicated in a laboratory fairly consistently due to the relatively high level of control that can be achieved in the industrial process. However, there are some issues with regard to how the process differs from country to country. In the UK, the composting process rarely runs beyond 90 days[21]—half of the time allowed for in the standard. This means that even where PAC plastic may pass EN 13432 within 6 months of treatment, it may not sufficiently biodegrade in practice in an industrial composting process designed with shorter residence times.

There are various certification schemes that use either EN 13432 or EN 14995 as the criteria for certification, and for the subsequent issuing of a label that can be displayed on the product. Vinçotte's OK compost certification and Din Certco 'seedling' mark are both well recognised for this, as reproduced in Figure 2. Vinçotte also certifies for home composting using EN13432 as a basis, but with reduced temperatures and increased time: this reflects the differences in home composting compared with industrial composting.

Other standards include ASTM D6400 from the US and DIN V 54900 from Germany both of which are less strict than EN 13432 and require only 60% (90% for copolymers) biodegradation in 6 months.

[21] DEFRA (2015) *Review of Standards for Biodegradable Plastic Carrier Bags*, December 2015.

Figure 2: Vinçotte and Din Certco Compost Certification Labels

3.2 Freshwater and Marine Standards

There are far fewer standards that cover biodegradation in water and there is currently no recommended standard at the European level.

The ASTM D7081 for *'Non-Floating Biodegradable Plastics in the Marine Environment'* is the most notable standard that covers the marine environment, although it has been withdrawn as of 2014, and no replacement has yet been accepted. The reason for withdrawal was due to the period of its validity—8 years—elapsing rather than specific issues with the methodology. There are currently no equivalent ISO or EN standards.

The test itself is similar in nature to the composting test, but with the samples suspended in 30°C sea water. The standard requires that 30% of the carbon in the test sample is converted to CO_2 after 180 days. This is much lower than is required for composting, but represents the level of biodegradation that is expected to occur when cellulose—the benchmark material for which materials are compared against for biodegradability—is used.

European standard 14987[22] is the closest to a freshwater standard with biodegradation targets. The scope of the standard is limited to the verification of whether a plastic material can be considered disposable in wastewater treatment plants. The test requires the use of bacteria taken from a wastewater treatment plant and is conducted at 20-25°C. It, therefore, ought only to be considered applicable to that specific environment. Nevertheless, the Vinçotte OK Biodegradable water label utilises the criteria set by the standard (90% biodegradation in 56 days) and requires the use of test standard ISO 14851[23] or ISO 14852.[24]

The OK Biodegradable marine label requires conformity to ASTM D7081, however it also requires a much stricter biodegradation target of 90% in 6 months. There are currently no PAC plastics certified by Vinçotte for either of the two aqueous labels, and only six[25] manufacturers of other plastics (all bio based) have been certified for fresh water, and one for marine water (also a bio based plastic polymer)—compared with 19 for soil. This is,

[22] EN 14987: Plastics. Evaluation of disposability in waste water treatment plants. Test scheme for final acceptance and specifications
[23] ISO 14851: Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium -- Method by measuring the oxygen demand in a closed respirometer
[24] ISO 14852: Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium -- Method by analysis of evolved carbon dioxide
[25] AIB-Vinçotte International (2016) *OK biodegradable Marine OK biodegradable Soil and OK biodegradable Water Conformity Marks*, 2016, http://www.okcompost.be/data/pdf-document/okb-mate.pdf

perhaps, an indication of how difficult it is to obtain certification for biodegradation in aqueous environments, even for products that achieve certification for biodegradation in soil. It may also reflect issues regarding the communication of marine biodegradability as Vinçotte specifically forbids marketing of the label for products that are frequently littered. There is a clear reluctance to allow the certification scheme to promote littering into the sea of materials that can biodegrade, but rather the intention is to verify the biodegradability claims of materials in the marine environment.

The science and understanding of marine biodegradability, and how to create reliable and representative laboratory tests for this, is in its infancy. This is, however, proceeding since the introduction of plastic into the sea—whether biodegradable or not—is a contentious issue. Whilst new test methods are being developed, such as ASTM D7991[26] for plastic buried in marine sediment, appropriate caution is being demonstrated due to the need to be certain of the effects before standards are agreed.

3.3 Soil Standards

In lieu of any standards which address the biodegradation in the open environment (i.e. land based littering), the closest proxy is probably to be found in soil burial standards. Whilst littered items may not be fully buried in soil, these standards give an indication of what conditions would be required for biodegradation in this environment.

There are currently no international standards for biodegradability in soil, although there are various international test methods such as ISO 17556[27] and ASTM D5988.[28] Both methods specify that the test is to be undertaken at 25°C, although ISO requires a 'standard' soil, whereas ASTM specifies that soil is to be collected from three diverse locations. It would, therefore, be difficult to accurately replicate results using the ASTM test, but it may also be more representative of local soil conditions—the balance between replicability and representativeness is a persistent challenge within all types of biodegradation test methods. The UK's DEFRA recently reviewed [29] the standards for biodegradable plastic bags. It found that ISO 17556 testing under accelerated conditions—temperatures of 25°C—and that measuring ultimate biodegradation were significant weaknesses in the standard when applying the findings to the open environment. It concluded that:

> *"More research and consensus would be required to establish methods for validating the application of laboratory tests for the conditions of the open environment [AND] definitive, evidence-based identification of acceptable ecologically and biologically relevant timeframes for the biodegradation of plastic films in the unmanaged terrestrial environment is currently lacking and continues to be controversial."*

The study highlights the need to develop a scientific consensus on how to effectively simulate biodegradation in unmanaged open environments. Currently, the use of soil

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[26] ASTM D7991: Standard Test Method for Determining Aerobic Biodegradation of Plastics Buried in Sandy Marine Sediment under Controlled Laboratory Conditions

[27] ISO 17556: Plastics –determination of the ultimate aerobic biodegradability of plastic materials in soil by measuring the oxygen demand in a respirometer or the amount of carbon dioxide evolved.

[28] ASTM D5988: Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials in Soil

[29] DEFRA (2015) *Review of Standards for Biodegradable Plastic Carrier Bags*, December 2015

biodegradability testing cannot guarantee that the same results will be gained outside of the narrow laboratory conditions.

French standard NFU 52 001[30] for agricultural mulching products is the most relevant *national* standard, with targets established for biodegradability in soil. It also requires tests to be conducted in compost and water, and requires a minimum biodegradation of 60% within one year for soil, and 90% within six months for water and compost. Interestingly, only two of the three targets are required to be met to achieve the standard, and soil medium does not necessarily need to be one of those two. Therefore, material can be compliant with this standard without the need to biodegrade in soil.

For the Vinçotte OK Biodegradable Soil label, either of the test methods from ISO or ASTM is deemed acceptable. Due to the lack of international standards, it has defined its own, and therefore requires a minimum of 90% biodegradability within 2 years buried in soil. This is comparable with the French standard for soil testing but for a longer test period.

A US specification (WK29802[31]) for biodegradation of plastics in soil is currently being developed by the ASTM. The scope is wide ranging and aimed at:

> *"…plastic materials that are designed to ultimately biodegrade when in contact with soil without diminishing the value or utility of the soil or creating any adverse impact on the environment via the degradation products."*

The specification is intended to establish the requirements for labelling of materials and products, including packaging made from plastics, as 'soil degradable'.

[30] NF U52-001: Biodegradable materials for use in agriculture and horticulture - Mulching products - Requirements and test methods

[31] ASTM Standard WK29802: New Specification for Virgin Plastics that biodegrade in Soil under Aerobic Laboratory Conditions

Table 1: Summary of Key Biodegradability Standards

Standard	Country	Test Method	Pass/Fail criteria	Environment	Biotic Degradation Test	Disintegration	Ecotoxicity
EN 13432/ 14995	Euro	✘ (uses EN 14855 method)	✓	Industrial Composting	• Aerobic- **90%** in 6 months • Anaerobic – **50%** in 2 months	• Aerobic – **90%** pass through a 2mm sieve after 3 months • Anaerobic- - **90%** pass through a 2mm sieve after 5 weeks	• **90%** plant germination compared with control. (OECD 208) • Limits on heavy metals
Vincotte OK Home	Euro	✘	✓	Home composting	• To EN 13432 but at 20-30°C for 1 year	• To EN 13432 • No material visible in compost after test	• To EN 13432
ASTM D7081	USA	✓	✓	Marine water	• **30%** in 6 months • Should also pass ASTM D6400 (industrial composting)	• **70%** pass through a 2mm sieve after 3 months	• Fish or algae toxicity test • Limits on heavy metals
EN 14987	Euro	✘ (uses ISO 14851 or 14852 method)	✓	Waste water	• **90%** after 56 days	• None	• None
Vincotte OK Home	Euro	✘	✓	Soil	• **90%** in 2 years	• None	• None
NF U52-001	France	✓	✓	• Water • Soil • Compost	• **90%** in 6 months • **60%** in 12 months • **90%** in 6 months	• None	• Plant and earthworm toxicity tests • Limits on heavy metals

3.4 Oxo-Biodegradation Standards

As well as the more general biodegradation standards, recently, several approaches have been developed in order to begin to standardise testing and develop certifications for PAC plastic. In these standards, the degradation process of PAC plastic is most often defined by three test methods (known as tiers in ASTM D6954) which are used successively in many of the other national standards:

1) **Tier 1 – Abiotic Degradation**
   The stage during which either heat or UV light (or both) is used to promote oxidation and subsequent fragmentation;
2) **Tier 2 – Biotic Degradation**
   The stage where previously abiotically degraded material is subjected to an environment where bacterial growth is promoted
3) **Tier 3 – Ecotoxicity**
   The final stage where the material is tested for toxicological impacts on flora and fauna.

The reason for the introduction of these approaches is that none of the existing biodegradation standards specify that a material must undergo the equivalent of a Tier 1 stage. Therefore, a PAC plastic would most likely fail to meet the test criteria since a vital first stage in the breakdown of PAC plastic (i.e. photo-oxidation) is missing in the biodegradation tests.

In this case, it is also important to highlight the difference between test methods, test criteria and standards. Whilst both ASTM D6954 and BS 8472 provide a framework for the testing of PAC plastic (i.e. a test method), they do not set pass/fail criteria. Therefore, there is no basis for accreditation, or compliance. These two approaches may, therefore, be considered as 'standardised testing methods', but they lack any kind of pass/fail test criterion. The term 'standard' is somewhat problematic in practice, due to its usage both as the standardised test method and also as the pass/fail performance level [if present].

The ATSM D6954 and BS 8472 test methods are used in Sweden and the UAE as guidance to perform the relevant tests. In the Swedish case, it is Standard SPCR 141 which specifies the degradation levels that must be reached [under BS 8472 or ASTM 6954 testing approaches] for the purposes of certification. France has also produced its own standard which provides pass/fail limits, but uses an entirely different methodology for evaluation.

Table 2 provides a summary of the requirements for each tier of each test standard.

Most approaches stipulate the use of an evolved carbon dioxide test which captures and measures the CO_2 released by the test sample during the biotic degradation test, which can be performed in soil, compost or aqueous media. The emission of CO_2 is compared with the theoretical carbon content of the material to ascertain the proportion that has biodegraded.

The French standard has taken a different approach to measuring biodegradability by measuring the ratio of adenosine di-phosphate (ADP) over adenosine tri-phosphate (ATP) of the bacteria that are placed on the sample. This test essentially measures the activity of the bacteria, with the theory being that, as the polymer is the only nutrition source, its activity would reduce over time if it cannot 'feed' on it. Similarly, if the polymer sample is toxic it would kill the bacteria. The use of this test method and its implications are discussed further in Section 4.1.3.

Table 2: Test and Accreditation Standards for PAC Plastics

Standard	Country	Test Method	Pass/Fail criteria	Abiotic Test	Biotic Degradation Test	Ecotoxicity Test
BS 8472	UK	✓	✗	• Exposure to photo/thermal oxidation 20-70°C • Simple physical embrittlement/fragmentation test	• Buried in soil at a concentration of 0.2%. • Test stopped once 50% of carbon mass has evolved.	• Partly evolved plastic is mixed with seeds • Germination is compared with control
ASTM D6954	USA	✓	✗	• Exposure to photo/thermal oxidation at 20-70°C • <5% elongation at break and molecular weight (MW) of <5,000	• Appropriate test environment used; soil, composting, or landfill. • Test stopped at 60% carbon evolution (90% for heteropolymers).	• Aqua toxicity, plant germination and earthworm toxicity tests performed on samples.
SPCR 141	Sweden	✓	✓	• Test to BS 8472 or ASTM 6954 • 70°C max **4 weeks** • <5% elongation at break and MW of <10,000	• Soil or fresh water test. • Must reach **90%** carbon evolution **within 24 months** or **60%** without plateau. • **90%** disintegration (<2mm) within **24 months**	• Partly evolved plastic is mixed with seeds • Germination is compared with control • Must reach **90%** for germination and biomass
AC T51-808	France	✓	✓	• Absorbance increase at 1 714 cm^{-1} ***OR*** • Elongation at break (both values differ based on film thickness and test conditions)	• ATP concentration 3x higher than control sample between 1 and 6 months • ADP/ATP ratio ≤ 3 after 180 days • Bacteria is still viable at end of test	Not included but implied in biodegradation tests
S5009	UAE	✓	✓	• Test to BS 8472 or ASTM 6954 • <5% elongation at break and MW of <5,000 in max **4 weeks**	• Test to BS 8472 or ASTM 6954 • **60 %** of the organic carbon must be converted to carbon dioxide within **6 months**.	• Heavy metal limits • No toxicity test included

3.4.1 BS 8472:2011 (UK)

"Methods for the assessment of the oxo-biodegradation of plastics and of the photo-toxicity of the residues in controlled laboratory conditions"

This British Standard provides a lose framework for the testing of PAC plastics. It gives guidance on how to test the material for abiotic degradation using either UV light or heat—a wide heating range of 20-70°C is specified and capped at 80°C. No specific recommendations are given as to which of these approaches to abiotic degradation is more appropriate. Simple physical bending, or rubbing between fingers, are used to test whether the sample is brittle or fragmented, and no further analysis of the state of the material is required to discern any changes to its character.

Soil biodegradation tests are performed on the degraded samples until 50% of the theoretical carbon content has evolved (using test methods from ISO 17556). A time limit for the test is not given, and at no point is it implied that this is, or is not, an acceptable level of degradation. This sample is then put through plant toxicity testing conforming to OECD 208.

Whilst a sample can be tested in accordance with these guidelines there are no pass/fail criteria for the degradation tests.

3.4.2 ASTM D6954 (USA)

"Exposing and Testing Plastics that Degrade in the Environment by a Combination of Oxidation and Biodegradation"

Similar to BS 8472, ASTM D6954 presents standardised guidance for a series of methodological tests without any performance level criteria. The method for measuring the abiotic stage (Tier 1) requires a more scientific approach than under BS 8472, with the resulting sample needing to reach a 5% elongation at break (i.e. a destructive stretch test where breakage occurs with the sample only having elongated to 105% of its original length) and a molecular weight (MW) of under 5,000 before biotic testing can commence. No time limits are specified for this. D6954 is also wider in scope as the biotic testing (Tier 2) can be performed in either soil, landfill or composting test conditions; the relevant ASTM standards are used to control these tests.

A degradation of 60% is required before the toxicity test (Tier 3) is carried out. This increases to 90% for materials consisting of more than one polymer. Tests to measure the effects on plant germination to OECD 208, as well as aquatic toxicity to ASTM E1440 and earthworm toxicity to OECD 207, are proposed.

Again, whilst this standard is greater in scope than BS 8472 and allows testing in a greater variety of conditions, it also does not provide pass/fail criteria.

3.4.3 SPCR 141 (Sweden)

"Certification rules for Classification for treatment of polymeric waste"

The Swedish standard builds upon both the BS and ASTM standards by adopting their test methods (and the tier system from ASTM D6954), but also introducing limits that the material must comply with in order to meet the standard, and display the appropriate certification. The abiotic test requires a higher molecular weight of 10,000 to be used in Tier 2 testing. It must also only be exposed to temperatures of 70°C for a maximum of 4 weeks.

Biotic testing is undertaken in either aqueous media (to ISO 14852) or within soil (to ISO 17556). In both cases, the sample must biodegrade by at least 90% within 24 months or reach 60% without reaching a plateau. According to the standard, this is regarded as proof that the material is biodegradable. A further requirement specifies that at least 90% of the sample must also have fragmented into pieces less than 2mm in size after the Tier 2 test.

The final tier 3 test uses OECD 208 guidelines on testing the germination and growth of plants. A requirement of more than 90% germination and biomass must be achieved when compared to the control.

3.4.4 AC T51-808 (France)

"Assessment of oxobiodegradability of polyolefinic materials in the form of films"

This is a voluntary standard from France that is specific to plastic films. It is the only other national standard—alongside Sweden's—that sets specific criteria that a test sample must reach.

The tests for both the abiotic and biotic stages of degradation differ from all other standards. For the biotic degradation stage, the carbonyl index is the form of measurement which is claimed as an accurate indicator of the level of oxidation in the sample material.[32] It is also the only standard to specify different levels that must be achieved based upon the intended use. This is an important distinction, as the defined purpose of the material will affect the chosen formulation of the additives. This is a significant omission from all of the other standards as it is important to align the test to the intended use, and make sure that the product can only be certified for those uses rather than for general, uncontrolled usage.

The second test—known as the ATP test—measures the biological activity of bacteria cells placed upon the sample. A positive test suggests that the bacteria are successfully feeding upon the sample. This also points to the conclusion that the plastic is also not toxic as the feeding bacteria would not survive. This test has yet to gain full acceptance with the PAC plastics industry and there appears to be little use of it outside France. Some of the issues with this test are discussed further in Section 4.1.3.

3.4.5 S5009 (UAE)

"Standard & Specification For Oxo-Biodegradation Of Plastic Bags And Other Disposable Plastic Objects."

Similar to SPCR 141 this standard from the UAE proposes following the test procedures of other standards such as ASTM D6954 and BS 8472 (although the latter was still in development when S5009 was released in 2009). Tier 1 testing is also specified to last no more than four weeks, but a lower molecular weight limit of 5,000 is necessary before the Tier 2 test can begin. Again, no specific test methods are specified, but the BS and ASTM standards are referred to. A much stricter criterion (compared to the Swedish standard) of 60% biodegradation over 6 months is set. A third tier test is not performed, but it is a requirement that heavy metals are limited within the source material.

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[32] When organic polymers oxidise, carbonyl and hydroxyl groups are amongst the most prevalent products. They are readily detectable through infrared spectroscopy.

4.0 Review of Key Issues

4.1 Issues of Biodegradability

Within the following subsections, five specific hypotheses relating to biodegradability of PAC plastics are interrogated with the aim of concluding, where possible, on whether the hypothesis can be supported or refuted.

4.1.1 Hypothesis 1: In open environments, oxo-biodegradable additives will accelerate the fragmentation of traditional polymers.

This hypothesis relates specifically to the abiotic degradation stage (Tier 1 in ASTM D6954) where the exposure to heat and/or UV light oxidises the PAC plastic to the point in which it becomes brittle and fragments. At this point it is also claimed that the PAC plastic is then ready to biodegrade. This is examined in hypotheses 2—5 for the various environments that these materials may end up in.

In 2010 the UK's Department for the Environment and Rural Affairs (DEFRA) commissioned a review of evidence[33] from Loughborough University which concluded that;

> *"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 reported."*

There are several methods which have been employed to analyse test samples for indications of abiotic degradation (oxidation). The main examples are as follows;

- Using an FTIR[34] to measure the carbonyl index (CO_i) as an indicator of oxygen uptake;
- Measuring an increase in weight as an indicator of oxygen uptake;
- Measuring the increase in wettability;
- Measuring the decrease in molecular weight using HT-GPC[35];
- Measuring the tensile strength/elongation at break;
- Measuring the Melt flow index (MFI).

All of these methods are destructive except for the FTIR approach, which means that subsequent biodegradation tests cannot usually be performed on the same abiotically degraded sample.

The abiotic degradation test methods usually involve heat and/or UV light exposure which simulates and accelerates real life conditions. According to PAC plastic industry

[33] DEFRA (2015) *Review of Standards for Biodegradable Plastic Carrier Bags*, December 2015

[34] FTIR - Fourier transform infrared spectroscopy. This device can be used to measure the infrared absorption of a material and identify carbonyl compounds.

[35] HT-GPC - High Temperature Gel Permeation Chromatography. A system for measuring the molecular weight of polymers.

representatives[36], under standard output UV lights at a temperature of around 60°C, each hour of pre-treatment is estimated to be equal to one day in the open environment. It must be recognised that this is an approximate indicative example, which can also vary depending upon localised conditions. Most accelerated UV weathering tests—ASTM G154[37] for example—use geographical areas such as Florida, Arizona or the South of France to be the equivalent heat and light conditions simulated within the laboratory tests. It is clear, therefore, that 1 day of exposure in this environment may be very different to 1 day in Northern Europe, for example. For this reason, the results of laboratory tests are best used in comparative evaluations between products rather than as absolutes. Nevertheless it is necessary to relate test results back to real life as far as possible in order to help decide whether the timescale for degradation is appropriate.

The most realistic way to measure the effects of UV degradation is to allow the product to degrade in real time in the environment where it will ultimately end up. Most of the time, this is neither practical nor time efficient especially when test methods and approaches are regularly changing based on new information. In the following review of literature in this field, and where the author has not given an indication of an equivalent real-life timeframe, the above assumption (1 hour = 1 day in a 'South of France' type environment) will be used to provide an indication of this.

A study by Chiellini from 2006[38] investigated the abiotic degradation of polyethylene film subjected to thermal aging at temperatures of 55°C and 70°C. As seen in Figure 3, a weight increase was observed for all samples at both temperatures. However, a larger dwell time of 7 to 15 days was experienced at 55°C, compared with 2 to 5 days at 70°C. Similar results were experienced with the measurement of the carbonyl index and molecular weight with an increase and decrease respectively—both indicators of increased oxidation. Humidity was also found to make a significant impact on the initial dwell period at both temperatures. At a relative humidity of 75% (compared with dry conditions) the dwell time was significantly increased and a plateau reached in a much shorter time.

The study also investigated whether fragmentation occurs with high levels of moisture present. The samples were submerged in tap water at 55°C, and fragmented within 28 days before sinking to the bottom.

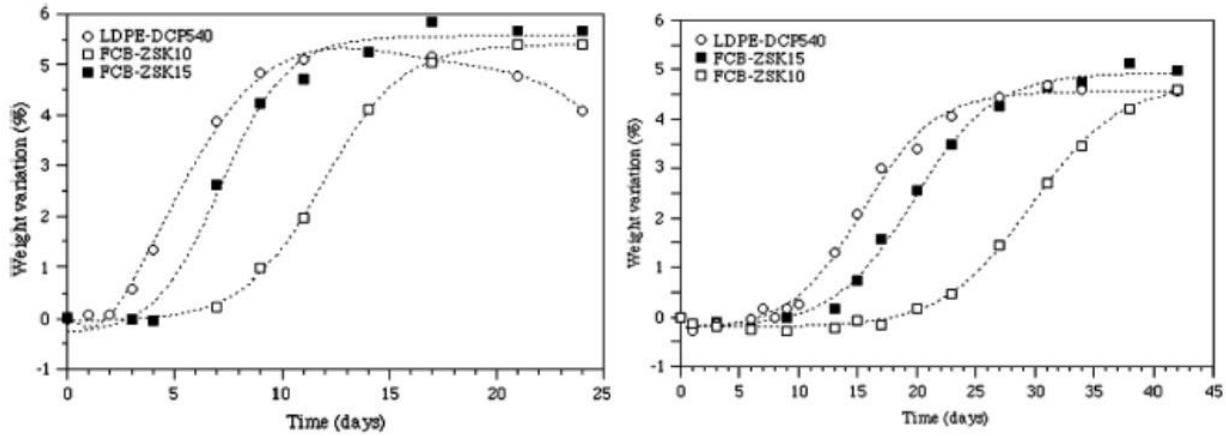
Whilst the overall results do suggest that fragmentation occurs, the circumstances of this test are very specific. The high temperatures accelerate the degradation process, but the study does not provide an estimate of an equivalent timeframe for fragmentation in open environments. The samples tested at 55°C plateaued at around 25 to 30 days so this would equate to around 600 to 720 days in the open environment, or around two years.

[36] Personal Communication with Philippe Michon, OPA and Perry Higgs, Symphony Environmental.

[37] ASTM G154: Standard Practice for Operating Fluorescent Ultraviolet (UV) Lamp Apparatus for Exposure of Nonmetallic Materials

[38] Chiellini, E., Corti, A., D'Antone, S., and Baciu, R. (2006) Oxo-biodegradable carbon backbone polymers – Oxidative degradation of polyethylene under accelerated test conditions, *Polymer Degradation and Stability*, Vol.91, No.11, pp.2739–2747

Figure 3: Weight Increase Over Time of PAC Plastic Samples at 70°C and 55°C



Source: Chiellini (2006)

A significant decrease in molecular weight is also used as an indicator of accelerated abiotic degradation. As identified in Section 3.4, standards ASTM D6954, SPCR 141 and S5009 all require the test sample to reach an average molecular weight of <5,000 (10,000 for SPCR 141). Where a time limit is specified, four weeks (672 hours) is the limit given. Several PAC plastics industry reports have been submitted as evidence for this.

Well's Plastics have commissioned two reports of this type for low density polyethylene (LDPE)[39] and polypropylene (PP)[40]. Whilst both studies were reportedly conducted under Tier 1 of ASTM D6954, with the LDPE study also specifying compliance with S5009 (UAE), the initial artificial aging was not conducted by the independent test house, but in-house at Wells plastics. The measurement of the molecular weight of five samples exposed to UV light for differing timescales was conducted by the independent test house. The results showed that average molecular weight of PAC LDPE reduced to below 5,000 in 14 days, and 40 days were required for this to be achieved by PAC PP. Assuming 1 hour = 1 day, the real life timeframe under ideal conditions would equate to 336 and 960 days respectively. This means that PAC LDPE would also pass the simulated 28 day limit set by S5009, but PAC PP would not; the S5009 standard may not have been available at the time of the (2009) test, however. The test lab report also points out that due to the small sample size the results may not be representative and therefore the relative differences between the samples should be the emphasis rather than the absolute values. On this basis the test does demonstrate that molecular weight is reduced over time through UV exposure, but how long this takes to result in fragmentation is not conclusive. Judging by the results of the tests, the timescale would be measured in years rather than days or months.

Whilst most laboratory and open environment tests have been undertaken to the guidelines of the various test standards, these invariably only determine abiotic degradation under controlled conditions designed to replicate the open environment. The question of whether

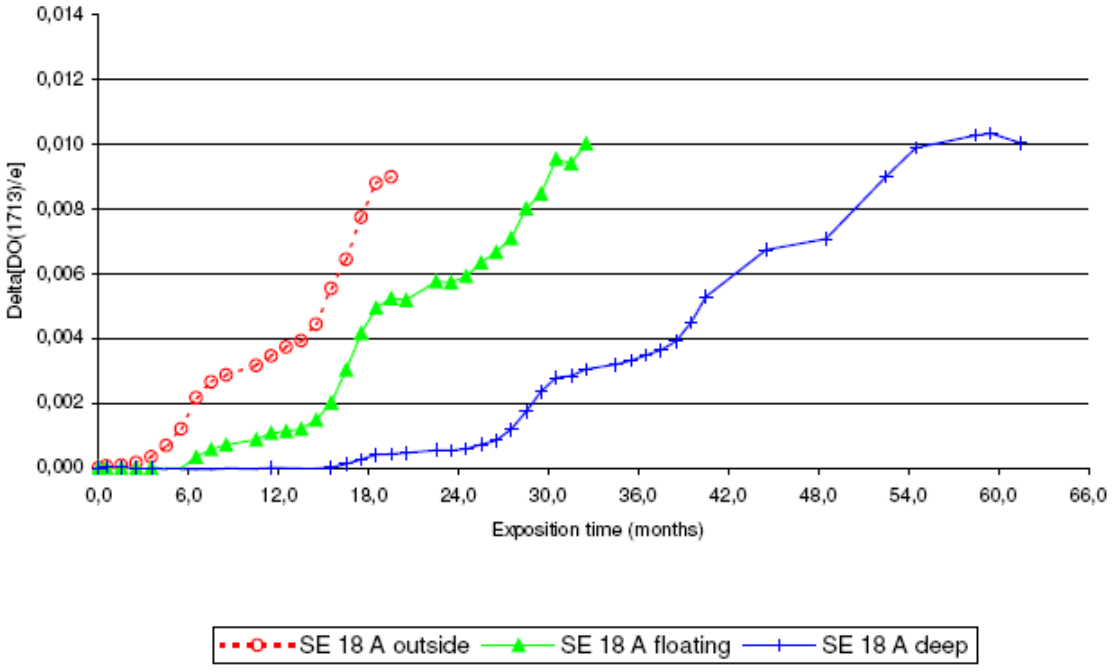
[39] Smithers Rapra (2010) *51806: Measurement of Average Molecular Weight by GPC as Required by ASTM D6954 Tier 1 and UAE S. No. 5009/2009 Section 5.3 Abiotic Degradation*, Report for Wells Plastic, July 2010
[40] Smithers Rapra (2009) *50967: Analysis of ASTM D6954 Tier 1 Aged Samples of Polypropylene*, Report for Wells Plastics, December 2009

PAC plastic behaves in the same way in other environments—especially aqueous ones—is also important to address.

Symphony Environmental have also commissioned testing to S5009 (UAE) by Intertek.[41] Again, this requires the molecular weight to fall below 5,000 within 28 days (672 hours). Three separate samples achieved this, but there was no conventional plastic used as a control for comparison. 400 hours (16 days) of testing showed the samples had reduced to a molecular weight of around 7,000.

The behaviour of PAC plastic in fresh water and sea water over extended periods is documented in a test report[42] by French accelerated weathering test centre, SEVAR, commissioned by additive producer Symphony Environmental. The test involved samples of PAC plastic placed in containers of both sea water and fresh water. The samples were placed 3cm above the water level (i.e. not in contact with water), on the surface and 40cm below the water surface. At regular periods the carbonyl index (CI) of the plastic was measured, to determine whether these environments still allowed the material to abiotically degrade (i.e. to embrittle and fragment).

Figure 4: Natural Test in Sea Water



Source: SEVAR

[41] Intertek (2013) *Characterisation of LDPE Polyethylene Film With 1% 93224/C ESMA 20213 Additive*, Report for Symphony Environmental Ltd, 2013

[42] SEVAR *Response of Polyethylene Films Containing Oxo-additive, When Submitted to Wet Environment (Sea and Fresh Water)*, Report for Symphony Environmental Ltd

Figure 4 shows the results of one of the test samples. A carbonyl index of 0.001 is considered by the PAC plastics industry[43] as the point in which PAC plastic fragments, and which also corresponds to a 50% loss in elongation at break. This limit is reached in around 6 months for PAC plastic not in contact with water. The floating plastic took a further six months and the deeply submerged sample took over two years to reach this state. As a point of reference, the PAC plastics industry[44] also consider a carbonyl index of 0.003 to be the point in which the PAC plastic has oxidised enough to biodegrade—this is explored further under subsequent hypotheses.

4.1.1.1 Conclusion

Hypothesis 1: In open environments, oxo-biodegradable additives will accelerate the fragmentation of traditional polymers.
Supported The evidence supports the hypothesis.
A summary of the evidence can be found in Table 3. Although the evidence supports that additives can be used to accelerate the fragmentation of plastic, this process appears to vary significantly depending upon the prevailing conditions. The varying amounts of: • heat; • light; and • moisture, all affect how quickly fragmentation occurs. Whilst this can be carefully controlled in a laboratory environment this is not the case for the open environment. These three factors can vary from one day to the next and the conditions are almost impossible to predict, especially given the range of situations that the PAC plastic might experience in the open environment. Therefore it is also very difficult to accurately predict the timescales in which a PAC plastic bag, for instance, will fragment if it is littered into the open environment. The speed and level of fragmentation are important factors in the overall biodegradability of the plastic, as discussed in hypotheses 2 to 5. Despite these difficulties it is evident that PAC plastic can abiotically degrade faster than plastic without additives when exposed to UV light and also, to a certain extent, by increased heat. Whereas timescales for this can vary based on the additive formulation, equivalent real life timescales appear to be measured in years rather than months or days before PAC plastic is sufficiently oxidised to demonstrate a molecular weight below a 5,000 yardstick which is often associated in the literature with a disposition for fragmentation.

[43] Personal Communication with Philippe Michon, OPA and Perry Higgs, Symphony Environmental
[44] Ibid

Table 3: Studies Testing the Abiotic Degradation of PAC plastics in the Open Environment

This summary table uses a crude colour grading system to indicate certain methodological strengths and weaknesses; from green to red indicating favoured to less-favoured.

Author	Peer Review	Additive (Supplier)	Number of Reps	Exposure	Time	Status
Kyrikou (2011)	Yes	Envirocare AG1000 (Ciba)	3	Real life cultivation conditions	105 days	Fragmentation evident
Briassoulis (2015)	Yes	Envirocare AG1000 (Ciba)	3	33 days UV @ 50°C	7 years	Fragmented
Chiellini (2006)	yes	TDPA (EPI Environment)	3	70°C and 50°C	26 – 60 days	Signs of fragmentation
Smithers Rapra (2010)	No	Reverte (Wells Plastics)	2	60°C	0 – 58 days	Mw of <5,000 in 14 days
SEVAR	No	d2w (Symphony)	1	Real life water contact	60 months	CI >0.001 after 1-2 years
Intertek (2013)	No	d2w (Symphony)	3	UV @ 50°C	0—672 hours	672 hour sample Mw of <5,000

4.1.2 Hypothesis 2: PAC plastics should not be considered compostable.

As identified in Section 3.1, the standard used throughout Europe to identify whether a packaging material if compostable is EN 13432[45]. The US equivalent is ASTM D6400. Both of these standards refer specifically to biodegradation in *industrial*[46] composting facilities. Also, Both EN 13432 and ASTM D6400 require that the plastics biodegrade by 90% within six months (180 days) in aerobic compost. There are potential issues with this, however, as in countries such as the UK the composting process rarely runs beyond 90 days.[47]

In 2010 the UK's Department for the Environment and Rural Affairs (DEFRA) commissioned a study[48] from Loughborough University where one of the areas of focus was a literature review into the evidence available for the compostability of PAC plastics. One of the study's main conclusions is as follows:

> *"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."*

In a response[49] to the Loughborough report, Symphony Environmental–a UK producer of pro-oxidant additives and founding member of the OPA–contend that:

> *"EN 13432, ASTM D6400 and the other standards for industrial compostability are not appropriate for testing oxo-biodegradable plastics because they are based on measuring the emission of carbon dioxide during degradation over a short timescale."*

Indeed, it appears that the PAC plastics industry claim that they have not made any claims to be compostable under EN13432, as demonstrated by a further industry response[50] to the Loughborough report (From UK producers EPI Europe, Symphony Environmental and Wells Plastics):

> *"…as far as we are aware, no reputable manufacturer makes claims of compostability for OBD [i.e. PAC] plastics. The most likely disposal routes for OBD [PAC] plastics are recycle, landfill and soil surface exposure/burial (litter and mulch films), so that degradation in soil contact or burial is more relevant."*

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[45] European Committee for Standardization (2000) *EN 13432 - Packaging - Requirements for Packaging Recoverable Through Composting and Biodegradation - Test Scheme and Evaluation Criteria for the Final Acceptance of Packaging*, 2000

[46] EN13432 states that it is aimed at "processing of packaging in controlled waste treatment plants but does not take into account packaging waste which may end up in the environment, through uncontrolled means, i.e. as litter" and ASTM D6400 states that it "covers plastics and products made from plastics that are designed to be composted in municipal and industrial aerobic composting facilities."

[47] DEFRA (2015) *Review of Standards for Biodegradable Plastic Carrier Bags*, December 2015

[48] DEFRA (2015) *Review of Standards for Biodegradable Plastic Carrier Bags*, December 2015

[49] Symphony Environmental (2010) *Response to Loughborough Report*, March 2010, http://www.biodeg.org/SYM%20RESPONSEto%20Loughboro%201.pdf

[50] EPI Europe, Symphony Environmental, and Wells Plastics (2011) *Industry Response to Dafra Report EVO 422*, April 2011

In another document[51] released by the OPA as part of evidence for the UK's environmental audit committee the following was stated:

> *"[bio-based carrier bags] were useful as garbage sacks for transporting organic matter to a composting plant, but oxo-bio bags have also been trialled and found satisfactory for this purpose."*

This appears to contradict the earlier industry response and suggests that they believe PAC plastic is suitable for composting. No other evidence is provided by the OPA to support that statement or what is considered to be 'satisfactory'.

The responses contend that too high an emphasis is placed on composting standards and that not meeting them is not a good indicator of whether a plastic material can acceptably biodegrade in other environments. Equally, the responses also suggest that plastics that are biodegradable in a composting environment may not be biodegradable in other environments. An example of Polylacticacid (PLA) is given, where it is suggested that whilst it biodegrades in industrial composting, it will not do so in dry soil or in home composting. No evidence is provided for this statement and whilst it implies that PAC plastic would biodegrade in these environments, no evidence is provided for this either.

It is unlikely that PAC plastic would be compliant with EN13432 due to the lack of provision for an abiotic degradation stage. For this reason it is important to differentiate between the studies which have used a pre-treatment and those that have not. It is therefore important to address two key issues in this regard:

- will the PAC plastic have enough time (and the right conditions) to degrade abiotically before entering the composting process? And,
- if it does have enough time, will it then subsequently biodegrade in a reasonable time frame?

The first proposition can, in part, be answered by the conclusions from Hypothesis 1. The time required to abiotically degrade to the point in which the material fragments and *may* be suitable for biodegradation is measured in years. Whilst it is also true that additives can be formulated to reduce this time, there is a danger of encroaching on the usable life of the product. Therefore, a theoretical product that is 'programmed' to degrade quicker to allow it to end up in composting may be compromised in use. This diminishing range of possible uses makes it unlikely that PAC plastic would be suitable for any application that involves composting at the end of the product's life. This is something that is recognised by the PAC plastics industry who do not promote their products for any such applications.

Despite this, it is useful to assess the literature evidence for biodegradation of PAC plastic in industrial composting. As this environment is at the top of the hierarchy of biodegradation, shown in Section 1.3, it may provide some insight into biodegradation behaviour further down the hierarchy in less aggressive environments.

[51] Oxo-Biodegradable Plastics Association (2014) *Supplementary Evidence to the Environmental Audit Committee Following the Hearing on 8th January 2014*, 2014

In 2003 Chiellini,[52,53] tested a sample of LDPE film which contained an additive from Canadian producer EPI Environment called Totally Degradable Plastic Additives (TDPA) which is added in quantities of 2 – 3%[54] to polymer resins. The additive concentration was not specified in the study, however. Chiellini also acknowledges that the work was performed on behalf of PAC plastics manufacturer EPI environment.

The degradation was calculated by capturing the released CO_2 and comparing that with the theoretical carbon content of the material. Initially, the material was subjected to a pre-treatment by thermally degrading in air in an oven at 55°C for 44 days to simulate the abiotic degradation phase necessary to allow biodegradation to occur—the stated equivalent of close to 3 years in the open environment.

Initially, tests were conducted in soil (see Section 4.1.3) but a further test was also conducted in compost with the temperature maintained at 55°C for seven days. After 420 days, the plastic had biodegraded by 28%.

In a study from 2011 by Jakubowicz[55] both soil and compost degradation tests were conducted on sample plastics with a prodegradant additive supplied by P-Life Japan Inc.[56] which is based on a manganese salt. After an initial pre-treatment at 65°C for ten days (a real life equivalent is not stated), the sample is then placed in soil maintained at 23°C. Compost degradation was conducted at 58°C following the initial pre-treatment. After 607 days the level of degradation was 43% although the standard deviation is large with one test degrading to around 30% and another to around 50%. It is unclear why such a large variation was found.

Feuilloley[57] conducted a number of tests in many environments to simulate the biodegradability of mulch films. Because of this, and unlike many of the other experiments, no pre-treatment was undertaken. The argument for this is that the mulch films would be partially buried during use and therefore not subject to extremes of UV radiation or temperature. It is unclear what the formulation of the pro-oxidant additive was, but mulch films are usually programmed to degrade slower so they are maintained intact for long enough to protect the crops. Almost no degradation was observed after compost testing for 50 days. However, other tests have already shown that this is well within the 'lag' period before degradation begins to accelerate.

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[52] Emo Chiellini, and Andrea Corti (2003) A Simple Method Suitable to Test the Ultimate Biodegradability of Environmentally Degradable Polymers, *Macromolecular Symposia*, Vol.197, No.1

[53] Chiellini, E., Corti, A., and Swift, G. (2003) Biodegradation of Thermally-oxidized, Fragmented Low-density Polyethylenes, *Polymer Degradation and Stability*, Vol.81, No.2, pp.341–351

[54] http://www.epi-global.com/en/products.php

[55] Jakubowicz, I., Yarahmadi, N., and Arthurson, V. (2011) Kinetics of Abiotic and Biotic Degradability of Low-density Polyethylene Containing Prodegradant Additives and its Effect on the Growth of Microbial Communities, *Polymer Degradation and Stability*, Vol.96, No.5, pp.919–928

[56] http://www.p-lifeasia.com/

[57] Feuilloley, P., César, G., Benguigui, L., et al. (2005) Degradation of Polyethylene Designed for Agricultural Purposes, *Journal of Polymers and the Environment*, Vol.13, No.4, pp.349–355

Similarly, in 2007, California State University[58] on behalf of California's Integrated Waste Management Board conducted bio-degradation tests on a range of bio-based materials in compost; also without applying any sort of pre-treatment. It tested plastic film containing EPI's TDPA – the same additive used in the Chiellini experiments, although the additive concentration or specific formulation is not disclosed. After 45 days only 2% biodegradation was found to have occurred through CO_2 monitoring. Before and after photos are shown in Figure 5 which demonstrates that a small amount of fragmentation has taken place, but not enough to signal that the PAC plastic would be ready to biodegrade significantly. This compares with the six other bio-based samples that all biodegraded by around 60% and an LDPE control sample that biodegraded by 1.7%. This is further evidence that the abiotic stage is required to allow PAC plastic to biodegrade in industrial composting.

Figure 5: PAC Plastic Before and After Composting (45 days)

Source: California State University (2007)

In 2009 Husarova[59] performed soil and composting degradation tests on two pre-treated LDPE films containing Add-X's AddiFlex pro-oxidant additive fragmented to below 2mm, with one of the samples also containing calcium carbonate as a filler. The samples were pre-treated at either 40°C or 80°C for 28 days in order to ascertain whether this would produce any difference during the biotic stage of degradation. No difference was discerned during simulated composting tests between the two differently pre-treated samples, with the maximum biodegradation (proportion of carbon mineralised as CO_2) found to be 19% after 460 days at 58°C, compared to a cellulose sample achieving around 28%. Under these composting test conditions the LDPE that did not contain calcium carbonate degraded more than the material that did; the reverse of the results from soil (see Section 4.1.3). It can be noted that 460 days at 58°C is beyond what may be expected in a typical commercial composting process.

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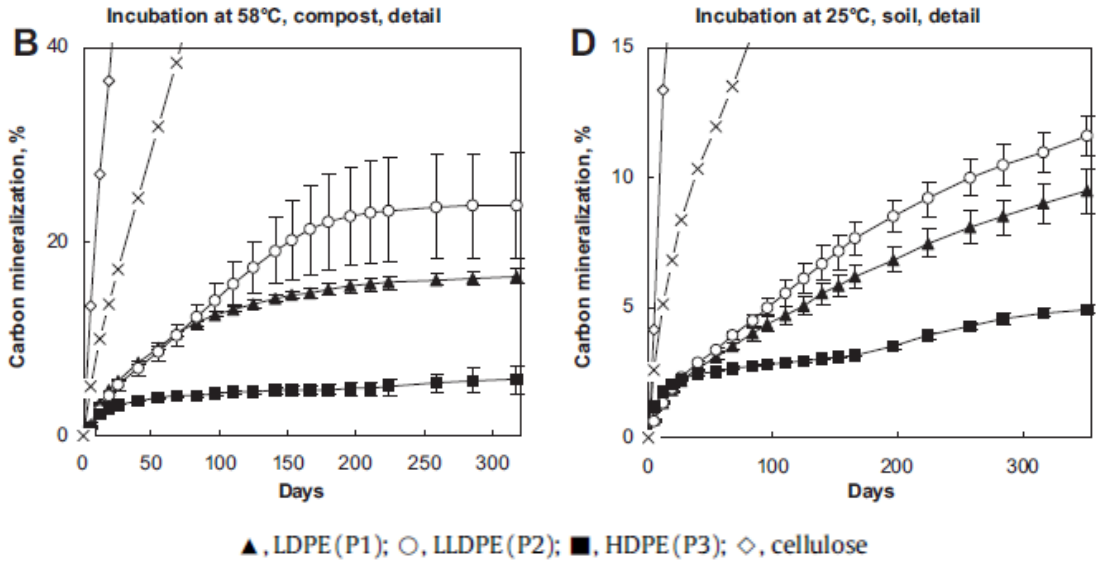
[58] California State University (2007) *Performance Evaluation of Environmentally Degradable Plastic Packaging and Disposable Food Service Ware - Final Report*, Report for California Integrated Waste Management Board, June 2007

[59] Husarova, L., Machovsky, M., Gerych, P., Houser, J., and Koutny, M. (2010) Aerobic biodegradation of calcium carbonate filled polyethylene film containing pro-oxidant additives, *Polymer Degradation and Stability*, Vol.95, No.9, pp.1794–1799

In 2010 Fontanella[60] studied three types of PAC plastics in simulated composting and soil environments using a different test method to the majority of the other papers on review. Instead of creating conditions that closely approximate real life conditions by using 'complex media' such as soils and composts with a diverse colony of microbes, Fontanella proposed a more controlled approach would be to use particular microbial strains and study their effects—a precursor to the ATP test that was introduced as part of the French T51-808 standard.

Samples were pre-treated thermally and with UV light to simulate around three years of outdoor weathering before being introduced to the microbes. The results found that in compost biodegradation was estimated at between 6 and 24 per cent over the course of a year (see Figure 6). LDPE biodegraded more than HPDE. The control material, cellulose, biodegraded completely.

Figure 6: Mineralisation of Three Types of PAC Plastic in Compost and Soil



Source: Fontella (2010)

Both Husarova and Fontanella found that composting was the more aggressive media when compared with soil. This is as one would expect from the elevated temperatures used during composting tests (~58°C), but is in contrast, however with the studies from Jakubowicz[61] and Chiellini[62] which found the opposite. It therefore appears that there is significant inconsistency in the results obtained between different studies.

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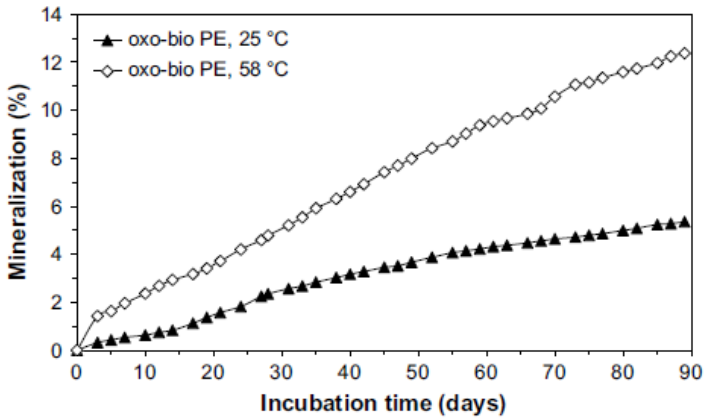
[60] Fontanella, S., Bonhomme, S., Koutny, M., et al. (2010) Comparison of the Biodegradability of Various Polyethylene Films Containing Pro-oxidant Additives, *Polymer Degradation and Stability*, Vol.95, No.6, pp.1011–1021

[61] Jakubowicz, I., Yarahmadi, N., and Arthurson, V. (2011) Kinetics of Abiotic and Biotic Degradability of Low-density Polyethylene Containing Prodegradant Additives and its Effect on the Growth of Microbial Communities, *Polymer Degradation and Stability*, Vol.96, No.5, pp.919–928

[62] Chiellini, E., Corti, A., and Swift, G. (2003) Biodegradation of Thermally-oxidized, Fragmented Low-density Polyethylenes, *Polymer Degradation and Stability*, Vol.81, No.2, pp.341–351

In 2009, Ojeda[63] utilised natural weathering over the course of a year to trigger the abiotic degradation process of PAC films provided by Symphony. The biotic biodegradation test was based on the methodology of Chiellini[64], but used two different temperatures of compost during testing. Figure 7 shows how the higher temperature compost produced over double the mineralisation of the lower temperature compost within the same timeframes, reaching 12.4% mineralisation in 90 days. Ojeda extrapolated that the maximum mineralisation potential (estimated by fitting the experimental data to an exponential equation) would be 23.2%. This suggests that, in the composting environment at least, a much lower mineralisation end point is reached for PAC plastic than would be required to meet EN13432 for aerobic composting (for instance), this being 90% biodegradation in 6 months. The study also found that exposure of PAC plastic to UV light via the sun had a significant impact on the amount of subsequent biodegradation. This can be seen in Figure 8 where the level of mineralization is three times greater after exposure to sun for 30 days compared with 7 days. It was found that exposure levels longer than 30 days did not substantially influence the level of biodegradation—this suggests that once the oxidation process is triggered, mineralisation can continue without further UV input.

Figure 7: Mineralisation of PAC Plastic in Compost at 25ºC and 58ºC

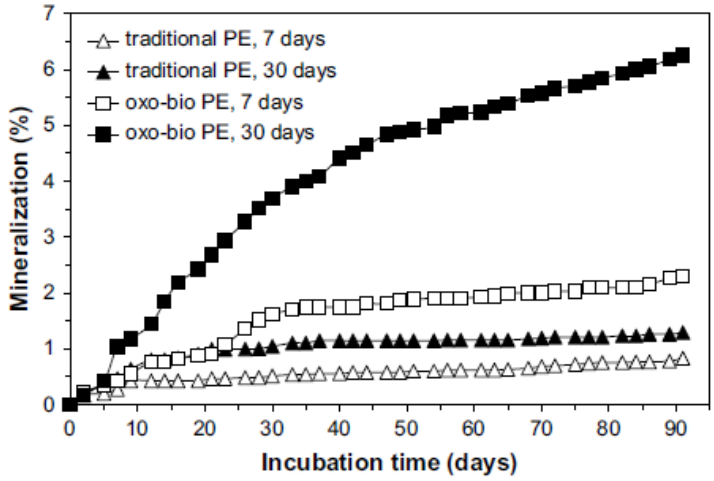


Source: Ojeda (2009)

[63] Ojeda, T.F.M., Dalmolin, E., Forte, M.M.C., Jacques, R.J.S., Bento, F.M., and Camargo, F.A.O. (2009) Abiotic and Biotic Degradation of Oxo-biodegradable Polyethylenes, *Polymer Degradation and Stability*, Vol.94, No.6, pp.965–970

[64] Chiellini, E., Corti, A., and Swift, G. (2003) Biodegradation of Thermally-oxidized, Fragmented Low-density Polyethylenes, *Polymer Degradation and Stability*, Vol.81, No.2, pp.341–351

Figure 8: Mineralisation of PAC Plastic in Compost After Sun Exposure (7 and 30 days)



Source: Ojeda (2009)

In 1999 Raninger et al. (including co-author representatives of EPI from Europe and Canada) conducted an experiment which is reported in the 2002 book 'Microbiology of Composting'.[65] The material tested included EPI's TDPA additive. The experiment consisted of real life testing in a municipal composting plant in Austria. Firstly, the shredded plastic film was mixed with screening rejects and left in the yard for two weeks. This was designed to simulate the abiotic phase of degradation. After this, it was mixed with source-separated organic biowaste from households to a concentration of 1%. This was then left in an indoor composting facility for six months.

The TDPA based film was reported to compost 'very well' as 63 per cent of the film was found to be biodegraded after 23 weeks (161 days). It is unclear from the reported methodology how this was measured, however.

The conclusion of the study is somewhat mixed, however, with the author stating that TDPA containing polyethylene;

> *"…meets the requirements to be classified as a degradable/compostable plastic and the compost end product is fully acceptable as land fertiliser."*

At the same time it is also stated that the plastic would not pas EN13432 as the material will not release 90% of the carbon as CO_2. The study argues that it performs similarly in this regard to 'natural' products such as chitin and lignin which would also not pass EN 13432.

One further observation made by the author, which is of relevance to this study is the conclusion that the 'intensive indoor maturation process' i.e. the composting process itself is not the decisive factor for effective degradability of PAC film. Instead, it is the initial (abiotic) process that is important, but as the author points out, this is also the least controllable element of the whole process in practice.

[65] Raninger (2002) Tests on Composting of Degradable Polyethylene in Respect to the Quality of the End Product Compost, *Microbiology of Composting* (2002) Heribert Insam: Springer Science & Business Media

A 2015 study undertaken by Michigan State University[66] attracted significant media interest, with several editorials[67, 68, 69] on the subject. These prompted statements from members of the PAC plastics industry[70,71] which dismissed their findings.

The experiments tested PE containing additives from three manufacturers—Reverte (Wells Plastics Ltd), Eco-one EL (Ecologic) d2w (Symphony)—for signs of biodegradation in simulated composting and landfill (discussed in Section 4.1.4) as well as real life soil burial tests (discussed in Section 4.1.3). The main PAC plastics industry criticism were that it is 'irrelevant' to test PAC plastic for biodegradation in either landfill or composting as it is already known that these products will not biodegrade in these environments—or at least not to any of the relevant standards. Despite such statements, this independent research and the premise of these experiments is not without merit.

All three manufacturers' samples were subjected to a laboratory composting tests without any form of pre-treatment. This resulted in no signs of biodegradation after 140 days for all samples except for the cellulose control. Next, a sample of Symphony's polyethylene was subjected to UV and heat treatment for 6.3 days—this is somewhat less than other tests have used and the author suggest this is the equivalent of 58 days in real life. Most other tests have used an equivalent real life exposure of 1 to 2 years. The resulting plastic had an elongation at break of 7% (very close to the 5% which is required under test standards for PAC plastic as specified in Table 2) whereby the author concluded that the plastic was of a low molecular weight, although this was not measured directly.

Figure 9 show that the pre-treated PAC plastic (dotted orange line) displayed negligible mineralisation after 140 days whereas cellulose had mineralised by around 70%. It can be interpreted that the percentage mineralisation results are calculated from comparing the CO_2 evolution results to those results for the blank sample; the mineralisation reversal for cellulose between around 60 and 100 days is not explained.

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[66] Selke, S., Auras, R., Nguyen, T.A., Castro Aguirre, E., Cheruvathur, R., and Liu, Y. (2015) Evaluation of Biodegradation-Promoting Additives for Plastics, *Environmental Science & Technology*, Vol.49, No.6, pp.3769–3777

[67] Karen Laird, Plastics Today (2015) *Biodegradation-Promoting Additives for Plastics Don't Work, Says Study*, accessed 1 June 2016, http://www.plasticstoday.com/biodegradation-promoting-additives-plastics-dont-work-says-study/41370511921901

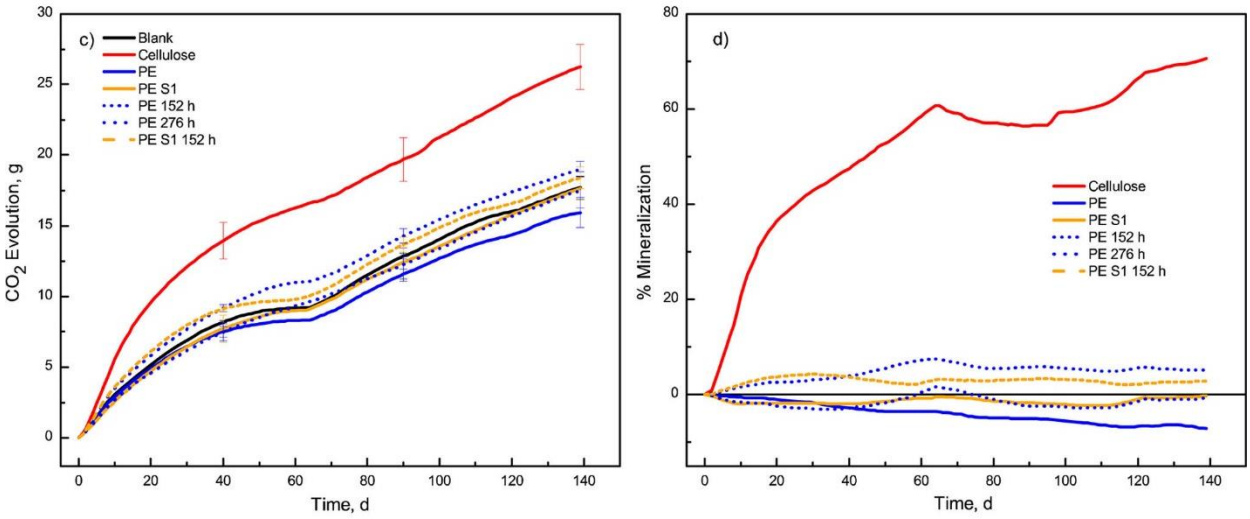
[68] Jenny Eagle, FoodQuality (2015) *Oxo-Biodegradable Plastics Association Claims MSU Study on Biodegradable Plastics is Misleading*, accessed 1 June 2016, http://www.foodqualitynews.com/R-D/OPA-refutes-MSU-study-on-biodegradable-plastics

[69] Waste Management World (2015) *Biodegradable Plastic Additives Dont Work, Claims MSU Study*, accessed 1 June 2016, https://waste-management-world.com/a/biodegradable-plastic-additives-dont-work-claims-msu-study

[70] EPI Environmental Plastics Inc. (2015) *Statement Re: 'Biodegradable Plastics Additives "Don't Work", Claims MSU Study" Published In Waste Management World, March 27, 2015'*, 2015, http://www.epi-global.com/files/epi_news/1428010553EPI_Response_to_MSU_Article_in_WMW.pdf

[71] Willow Ridge Plastics, Inc. (2015) *Statement Re: 'Evaluation of Biodegradation-Promoting Additives for Plastics', published in Environmental Science & Technology, February 27, 2015*, 2015, http://www.willowridgeplastics.com/MSU-Study-Response.pdf

Figure 9: Biodegradation of PAC Plastic in Compost Samples



Source: Selke (2015) [72]
'PE S1 152 h' = pre-treated PAC plastic, 'PE S1' = non pre-treated PAC plastic, others not containing any prodegradant additives.

Finally, in 2008, Reddy et al[73] studied the effects of specific bacteria on pre-treated PAC plastic samples. The pre-treatment consisted of oven heating at 70°C for 14 days which the author attributes to the equivalent of 4 years outside. The bacteria *P. aeruginosa*—o common bacteria found in compost—was used to inoculate the samples. Whilst the level of biodegradation was not measured throughout the experiment, both the carbonyl index and the molecular weight were. As seen in Figure 10 the molecular weight actually changes during the time in which the bacteria is present on the sample. The molecular weight is a calculation of the *average* over a sample so there will be areas where the molecular weight is higher and areas which are lower—demonstrated by the bell curve in Figure 10. These results indicate that the bacteria is only bio-assimilating the lower molecular weight fractions, which pushes the average of the remaining sample higher (line indicated as 'after 6 weeks biodegradation'), and that it is not able to 'perturb' high molecular weight fractions. The study also notes that the action of the microorganisms is only on the surface of the polymer. The paper provides some useful commentary on the biodegradation action of PAC plastic:

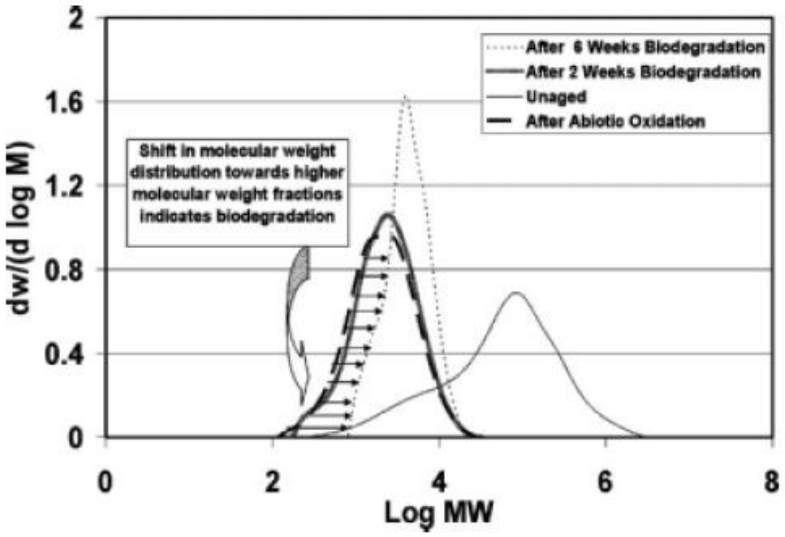
> *"The results […] reveal that biodegradation is mainly because of the consumption of pro-oxidant aided oxidation products. The shift toward high molecular weight during biodegradation also suggests that pro-oxidant has ceased its action during the abiotic oxidation stage and is not helping the biodegradation. The results substantiate the oxo-biodegradation theory […] which suggests that an increase in the abiotic oxidation levels and consequent decrease in the average molecular weight*

[72] Selke, S., Auras, R., Nguyen, T.A., Castro Aguirre, E., Cheruvathur, R., and Liu, Y. (2015) Evaluation of Biodegradation-Promoting Additives for Plastics, *Environmental Science & Technology*, Vol.49, No.6, pp.3769–3777

[73] Reddy, M.M., Deighton, M., Gupta, R.K., Bhattacharya, S.N., and Parthasarathy, R. (2009) Biodegradation of Oxo-biodegradable Polyethylene, *Journal of Applied Polymer Science*, Vol.111, No.3, pp.1426–1432

to under 5000 Da are required for achieving significant biodegradation in a reasonable time period. […] It has been proven that if the oxidized polyethylene has a molecular weight less than 5000 Da, a significant fraction of it will be in the range of 1000–2000 Da and this fraction can be rapidly biodegraded. The vacancies produced due to biodegradation can then cause swelling and relaxation of the whole material structure, which will facilitate diffusion of water and soluble compounds inside and thereby, substantially accelerating the biodegradation."

Figure 10: Molecular Weight Changes during Biodegradation



Source: Reddy (2009) [74]

4.1.2.1 Conclusion

Hypothesis 2: PAC plastics should not be considered compostable.
Supported. The PAC plastics industry generally avoids making claims that PAC plastic is compostable, which holds with the scientific evidence.
It should be understood that PAC plastics manufacturers are not known to claim or promote their products as capable of making PE biodegradable in compost to EN 13432. On the contrary, they recognise and promote the idea that composting is not a suitable disposal environment for their products. One measure which can be used as a gauge to composting is the percentage mineralisation of the material within a specific timeframe (for instance 90% mineralisation within 6 months, as discussed in Section 3.1). The scientific evidence suggests that whilst there is a small amount of biodegradation that takes place during industrial composting there are a number of conditions that affect the ability of PAC

[74] Ibid

plastic to fully biodegrade and meet relevant standards in the timeframe required during the composting process. Ojeda found that high temperatures have a significant positive impact of the level of biodegradation. This suggests that more rapid degradation may be achievable in commercial composting compared to home composting, although commercially driven time constraints are less relevant to the latter situation.

A summary of the relevant studies and their results is shown in Table 4. The most biodegradation identified was by Raninger and Steiner; however, the methodology employed to measure this is not clear and it is not known whether a peer review took place. The next highest level was found by Jakubowicz in a 2011 journal publication. With a pre-treatment of 10 days and three replications the methodology appears to be sound. Measured using CO_2 production, total biodegradation (considered as percentage mineralisation of the PAC plastic sample) was at 43% over the course of 607 days (subsequent to a heat based pre-treatment of unspecified real life equivalence). This is well below the amount necessary for EN 13432 certification (90% at 180 days) despite being subjected to UV pre-treatment. It should also be considered that because EN 13432 does not specify pre-treatment to simulate abiotic degradation, there is no possibility of PAC plastic passing this test. Equally, even with the introduction of pre-treatment the biodegradation times are nowhere near fast enough to satisfy the short timescales of industrial composting and to ensure amounts of un-degraded residues are negligible, so that any build-up of such materials in soils after continued application of composts is prevented.

Home composting environments have not been specifically tested, however the only certification available is an extension of the EN13432 by Vinçotte which specifies 90% biodegradation within 1 year. As the best observed biodegradation in industrial composting is half that in almost double the time, it is unlikely that PAC plastic could reach this target even if an abiotic test were to be included. Again, the PAC plastics industry make no claims that PAC plastic is home compostable. Nonetheless, like with industrial composting, it is clear that it is not the test standards that are barring this, but the unsuitability of the material for these specific processes.

It is therefore inappropriate to promote the use of PAC plastic for any purpose related to composting or (by extension from the conclusions to hypothesis 4) to AD. This would preclude its use as a container for organic waste that is destined for these processes. Any form of guidance that can be offered at an EU level to this end would potentially help those who are in a position to specify products for this purpose.

Table 4: Studies Testing the Biodegradability of PAC Plastics in Industrial Composting Conditions

This summary table uses a crude colour grading system to indicate certain methodological strengths and weaknesses; from green to red indicating favoured to less-favoured.

Author	Peer Review	Additive (Supplier)	Pre-treatment	Number of Reps	Degradation	Status	Time
Elevated Temperature Compost (~58°C)							
Husarova (2009)	Yes	AddiFlex (Add-X Biotech)	40—80 days @ 70°C	3	19%	Stopped Degrading	460 days
California Univ (2007)	No	TDPA (EPI Environment)	None	3	2%	Stopped Degrading	45 days
Feuilloley (2005)	Yes	Actimais (Trioplast)	None	1	1.1%	-	50 days
Chiellini (2003)	Yes	TDPA (EPI Environment)	44 days @ 55°C	3	28%	Slowly Increasing	430 days
Fontanella (2010)	Yes	Not Specified	3 years outdoor	3	6 – 24%	Stopped Degrading	317 days
Ojeda (2009)	Yes	d2w (Symphony)	1 years outdoor	3	12.4%	Slowly Increasing	90 days
Jakubowicz (2011)	Yes	P-Life (P-Life Japan)	10 days @ 65°C	3	43%	Stopped Degrading	607 days
Raninger and Steiner	Unknown	TDPA (EPI Environment)	2 weeks outdoors	1	63%	Unknown	161 days
Selke (Michigan Univ) (2015)	Yes	d2w (Symphony)	6.3 days @ 60°C + UV	2	>5%	Stopped Degrading	140 days
Reddy (2008)	Yes	Unknown	14 days @ 70°C	unknown	Evidence of biodegradation	-	60 days

4.1.3 Hypothesis 3: In open environments, PAC plastics biodegrade following their fragmentation.

In the context of this study the term "open environment" primarily refers to uncontrolled depositing of the plastic on land. In practice this is mostly in the form of littering or mismanaged waste. The conditions for any possible degradation are therefore not controlled and can vary widely. Within this report we extend the term "open environment" to include PAC mulch films. Whilst these are a different application to the carrier bag, some of the evidence is applicable and relevant to help understand how PAC plastic behaves in soil. Mulch films are widely used as a protective covering in commercial agriculture to help provide improved conditions for crop growth by reducing weeds, maintaining moisture and protecting from extremes of temperature. They were created in answer to the problem of the disposal of conventional polyethylene mulch films which are difficult to recover, almost impossible to recycle due to contamination and cannot (legally) be incorporated into the soil.[75] Whilst these films could be described as 'managed' this process usually involves ploughing the films back into the soil once the crop is harvested. After this is completed, there are no additional environmental controls—unlike composting—which can be used to manage and moderate the conditions experienced by the films. Comparing mulch films to plastic bags, the former is designed to be incorporated into soil whereas the latter ends up in soil as a result of a failure in waste management—including littering.

The lack of conditions control does mean that it is difficult to study biodegradation in these open environments. Soil type and their bacteria populations, as well as climate and moisture levels all contribute to the degradation process and are extremely variable. This means that it is difficult to generalise laboratory test results. There are also an increasing number of test methods being used, some of which are linked to ASTM or ISO test standards. This adds further difficulty to the comparison of results across different test methods.

In 2003, on behalf of Canadian PAC plastic producer EPI Environment, Chiellini[76,77] tested a sample of LDPE film which contained an additive from EPI Environment called Totally Degradable Plastic Additives (TDPA) which is added in quantities of 2 – 3%[78] to polymer resins. The additive concentration was not specified in the study, however. The results showed that between 49% and 63% mineralization occurred after approximately 600 days incubation. This is shown in Figure 11 where two different concentrations of LDPE to soil were tested—70 mg/g soil, (Q1) and 35 mg/g soil (Q2)—along with a paper control sample. Less than 5% degradation was recorded during the first 150 days (this is often referred to as the 'lag phase'); thereafter an exponential increase saw the samples degrade significantly.

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[75] Briassoulis, D., Miltiadis Hiskakis, Epifaneia Babou, and Ioanna Kyrikou (2014) Analysis of Long-term Degradation Behaviour of Polyethylene Mulching Films with Pro-oxidants under Real Cultivation and Soil Burial Conditions, *Environmental Science and Pollution Research*, Vol.22, No.4, pp.2584–2598

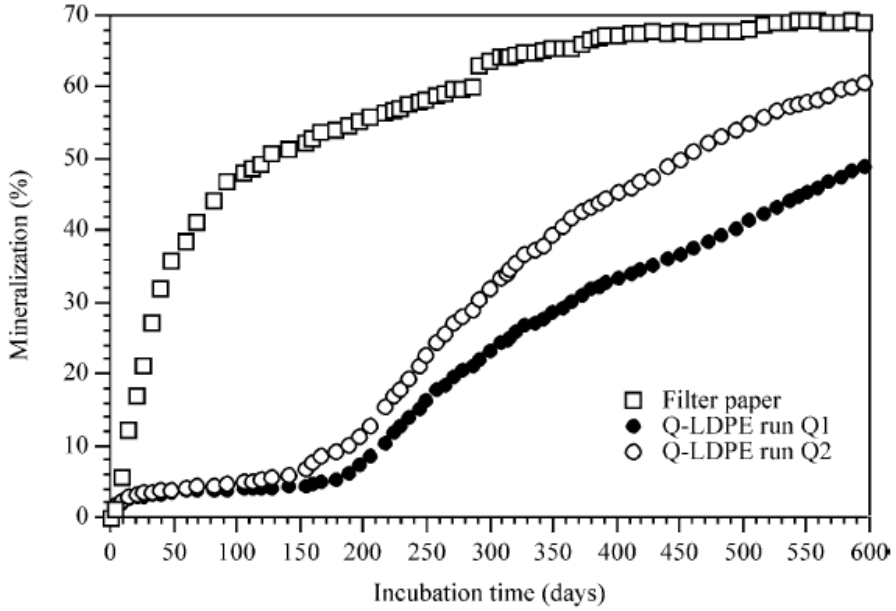
[76] Emo Chiellini, and Andrea Corti (2003) A Simple Method Suitable to Test the Ultimate Biodegradability of Environmentally Degradable Polymers, *Macromolecular Symposia*, Vol.197, No.1

[77] Chiellini, E., Corti, A., and Swift, G. (2003) Biodegradation of Thermally-oxidized, Fragmented Low-density Polyethylenes, *Polymer Degradation and Stability*, Vol.81, No.2, pp.341–351

[78] http://www.epi-global.com/en/products.php

However, the authors suggested that this may have been initiated by the introduction of distilled water to both Q1 and Q2 and 5g of fresh forest soil to Q2.

Figure 11: Mineralisation of PAC plastic in Soil - 70 mg/g soil, (Q1) and 35 mg/g soil (Q2)



Source: Chiellini (2003) [79]

In a study by Jakubowicz[80] from 2003, material was supplied by EKM Produktentwicklung to test its degradation in soil. The material was pre-treated at 70°C for 28 days—a significantly higher temperature and for a longer duration than most of the other tests. The soil was also maintained at 60°C which is also well above the ambient temperature used in most other studies. This resulted in a mineralisation of the material at between 60% and 65% in 200 days. The author proposes that complete mineralisation would eventually occur, though a timeframe for this is not suggested nor further supported by justification.

In a later study from 2011, also by Jakubowicz[81], soil and compost degradation tests were conducted on sample plastics with a prodegradant additive supplied by P-Life Japan Inc.[82], based upon a manganese salt. After an initial pre-treatment at 65°C for ten days which dropped the weight average molar mass to 8,800 (the real life equivalent time is not identified) the samples were then placed in soil maintained at 23°C. Similarly to Chiellini, a lag phase was observed, but also three further phases were identified:

- **Lag Phase** — 5% degradation up until 180 days;

[79] Chiellini, E., Corti, A., and Swift, G. (2003) Biodegradation of Thermally-oxidized, Fragmented Low-density Polyethylenes, *Polymer Degradation and Stability*, Vol.81, No.2, pp.341–351
[80] Jakubowicz, I. (2003) Evaluation of Degradability of Biodegradable Polyethylene (PE), *Polymer Degradation and Stability*, Vol.80, No.1, pp.39–43
[81] Jakubowicz, I., Yarahmadi, N., and Arthurson, V. (2011) Kinetics of Abiotic and Biotic Degradability of Low-density Polyethylene Containing Prodegradant Additives and its Effect on the Growth of Microbial Communities, *Polymer Degradation and Stability*, Vol.96, No.5, pp.919–928
[82] http://www.p-lifeasia.com/

- **Exponential Phase** – 20-22% degradation up until 360 days;
- **Classical Phase** – Linear increases up until 560 days;
- **Saturation Phase** – Beyond 560 days.

These results were found to be similar to Chiellini despite only adding water; whereas Chiellini also added fresh soil just before the exponential phase. The authors suggest that the addition of fresh soil was not therefore, a necessary condition. Three samples were tested in the Jakubowicz (2011) study with the mean biodegradation at 733 days calculated at 91%. It is thus stated that *"…it is possible to create LDPE-based materials that will almost completely biodegrade in soil within two years. It also indicates that the risk of plastic fragments remaining in soil indefinitely is very low."*

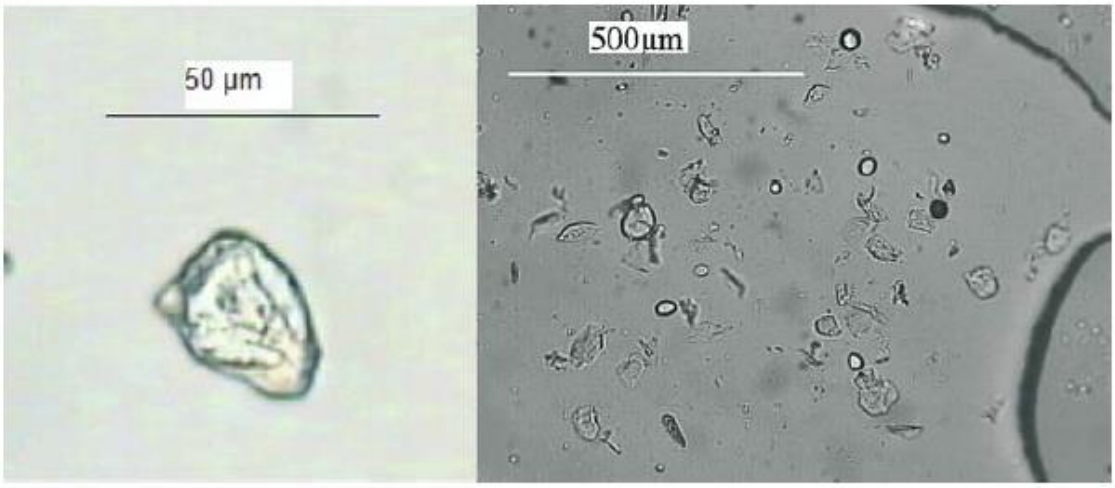
The key difference between Jakubowicz's 2003 and 2011 studies are the sample materials in question. In 2003 the sample had an 'activation energy' of 106 kJ/mol which is said to equate to a service life under 25°C indoor conditions of 4.5 years for one sample, and 2.5 years for another with twice the prodegradant content, before its molecular weight reduces to below 10,000 through abiotic degradation. In the 2011 study, the samples only required an activation energy of 84kJ/mol. It is not properly defined what service life period this may equate to, although it is stated that with a pre-treatment *"lifetime of one week at 70°C, the predicted lifetime at 23°C will be about two years for the material with an activation energy of 84 kJ/mol […] or seven years if the material has an activation energy of 106 kJ/mol"*. This suggests that the 84 kJ/mol sample's service life under typical indoor conditions is a fraction of the 106 kJ/mol sample; it might be that the 2.5 to 4.5 year life period from above can be factored down to between 0.7 and 1.3 years. This demonstrates the potentially significant differences between how the various additive formulations and concentrations (not to mention the anti-oxidant package and real life heat / moisture / UV exposure) can affect the degradation to lower molecular weights, resulting from oxidation during the abiotic phase.

As identified in Section 4.1.2, Feuilloley[83] conducted a number of tests in many environments to simulate the biodegradability of mulch films with no pre-treatment. Almost no degradation was observed for soil testing after 840 days.

The study also looked at agricultural land where mulch films had been used two years earlier and found—through visual observation—that 90% of the films had biodegraded. Further analysis showed, however, that there were significant micro-fragments present from 5 to70 µm in size (Figure 12). The study could not quantify what proportion of the mulch films that were applied to the land these fragments accounted for, but they were positively identified as PAC plastic. With microplastics defined as plastic smaller than 1mm, this can be viewed as microplastics within soil.

[83] Feuilloley, P., César, G., Benguigui, L., et al. (2005) Degradation of Polyethylene Designed for Agricultural Purposes, *Journal of Polymers and the Environment*, Vol.13, No.4, pp.349–355

Figure 12: PAC Plastic Residue from Mulch Film Application (2 years)



Source: Feuilloley (2015)

A peer reviewed paper[84] by lead author Demetres Briassoulis, a Professor at Agricultural University of Athens, was released in 2014. The paper focused on the degradation of mulch films for agricultural use and was a continuation of a study by Kyrikou (2011)[85] which looked at the abiotic or photo-chemical degradation of the PAC mulch films. This new study found that whilst the PE exhibited rapid UV induced degradation in both a laboratory and under real field cultivation conditions, significant plastic fragments remained after the cultivation period of 15 weeks. The samples demonstrated a reduction of their elongation at break of 50%, indicating a reduction in mechanical properties ultimately associated with low molecular weight, fragmentation and a precursor to biodegradation.

The material used contained a pro-oxidant additive called Envirocare by Ciba Chemicals. Ciba has since been acquired by BASF in 2008 and the company brand is no longer used. Envirocare was also discontinued by BASF in 2010 in favour of developing the Ecoflex and Ecovio products – the former a fossil based and latter a bio-based plastic.[86] Both are EN 13432 certified as compostable.

The films used in Briassoulis's experiment were subsequently buried under soil (as one would expect the field is rototilled after cultivation has ended) for a period of 8.5 years with periodic status checks at seven and eight years. Despite the plastics fragmenting further, with the elongation at break also reducing to the point where immediate onset of fragmentation is expected to occur, much of the film was found to still be intact. This can be seen from the photographs in Figure 13. Briassoulis further observed that although the

[84] Briassoulis, D., Miltiadis Hiskakis, Epifaneia Babou, and Ioanna Kyrikou (2014) Analysis of Long-term Degradation Behaviour of Polyethylene Mulching Films with Pro-oxidants under Real Cultivation and Soil Burial Conditions, *Environmental Science and Pollution Research*, Vol.22, No.4, pp.2584–2598

[85] Kyrikou, I., Briassoulis, D., Hiskakis, M., and Babou, E. (2011) Analysis of Photo-chemical Degradation Behaviour of Polyethylene Mulching Film with Pro-oxidants, *Polymer Degradation and Stability*, Vol.96, pp.2237–2252

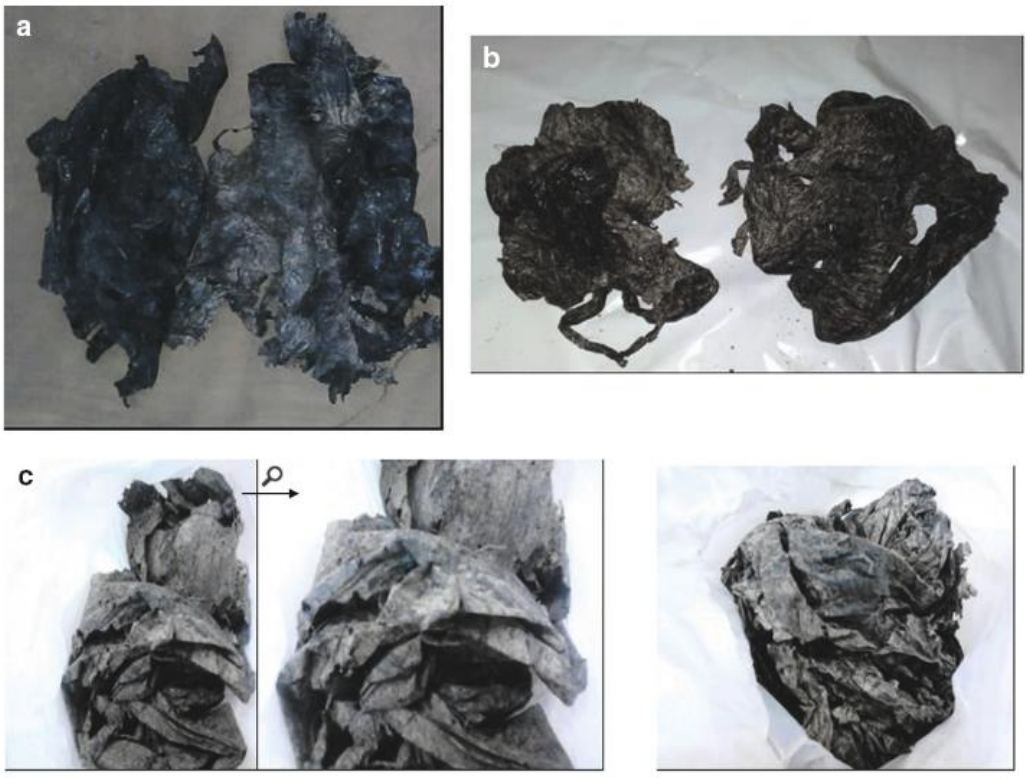
[86] http://www.agro.basf.com/agr/AP-Internet/en_GB/content/news_room/news/basf-focuses-on-ecovio-and-ecoflex

initial cultivation period saw an increase in the Carbonyl Index for the two PAC plastics on test, the buried samples showed a value close to zero—as seen in Figure 14 (the sample represented by the red bars contained slightly more UV stabiliser). The reduction was thought to be the result of the carboxylic acids leaching out of the plastic, but is evidence that an increase in the Carbonyl Index in the early stages of abiotic degradation does not invariably result in accelerated biodegradation.

Soil burial tests were also conducted by Michigan University[87] for PAC plastic from Symphony and Well. No pre-treatment was used to degrade the samples before they were buried in soil. The samples were buried for 1,095 days after which no visible disintegration was observed. The elongation at break was reduced by around 50% for the PAC polyethylene, but the conventional plastic control also displayed the same physical changes. This further confirms that the presence of the pro-oxidant additive does not have a significant effect on the plastic if it has not been subjected to UV triggered abiotic degradation.

Figure 13: Remains of Buried PAC Plastic Film

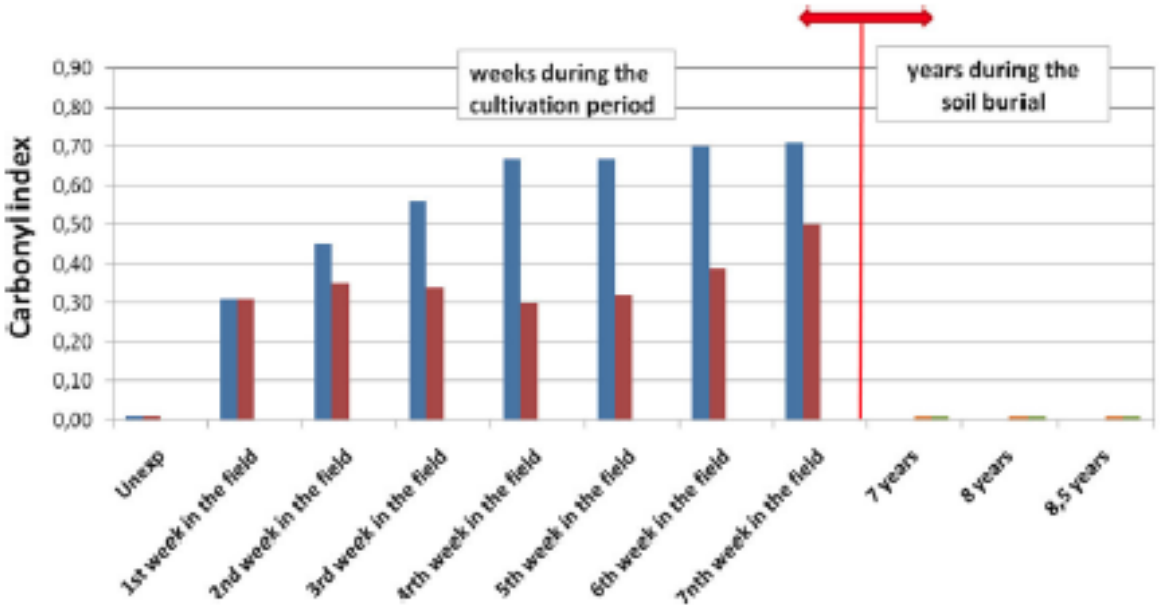
A: 7 years, B: 8 years C: 8.5 years



Source: Briassoulis (2014)

[87] Selke, S., Auras, R., Nguyen, T.A., Castro Aguirre, E., Cheruvathur, R., and Liu, Y. (2015) Evaluation of Biodegradation-Promoting Additives for Plastics, *Environmental Science & Technology*, Vol.49, No.6, pp.3769–3777

Figure 14: Carbonyl index of Cultivated Mulch Films

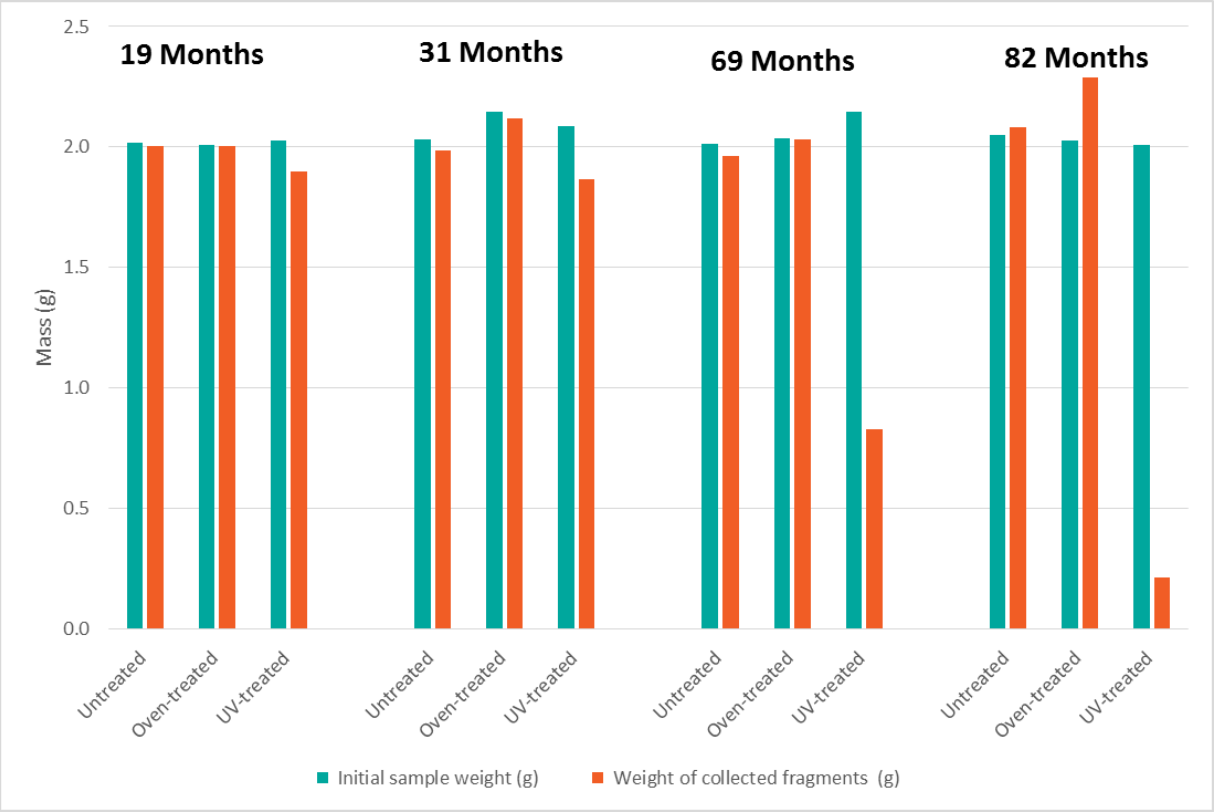


Source: Briassoulis (2014)

Concurrently with his previous study, Briassoulis[88] also investigated PAC plastic artificially aged with heat or UV light to accelerate the fragmentation process, before being buried for seven years. One sample was subjected to UVA and UVB rays for 800 hours (33 days) which the author suggests is greater than the radiation that would be given by the sun; no equivalent real life time period is given by the author although it was expected to simulate 'decades'. The second sample was subjected to 50°C heat only and a third was left untreated.

[88] Briassoulis, D., Hiskakis, M., Babou, E., and Kyrikou, I. (2015) Degradation in Soil Behavior of Artificially Aged Polyethylene Films with Pro-oxidants, *J. APPL. POLYM. SCI*

Figure 15: Evolution of the Weight from Samples Buried in Soil

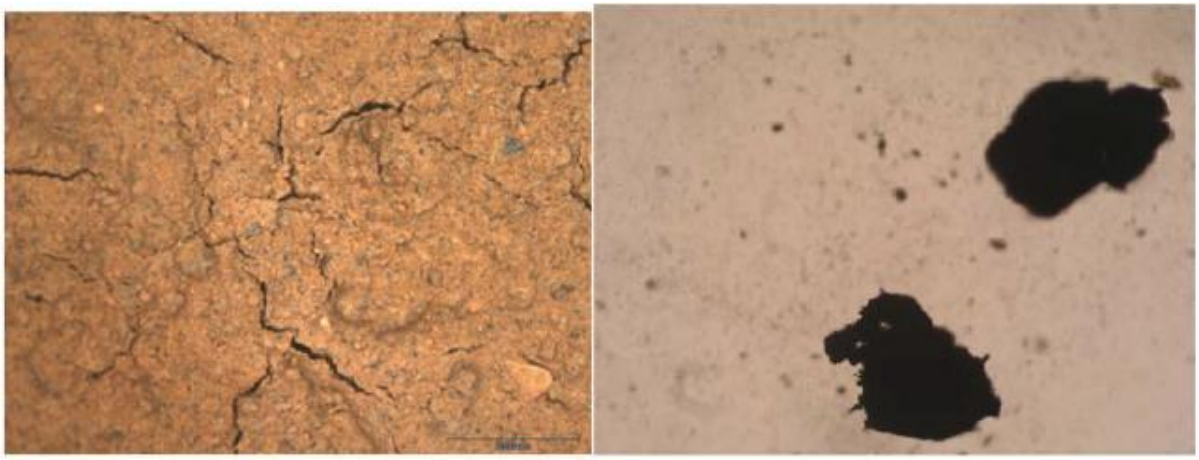


Source: Derived from Briassoulis (2015)

Figure 15 shows one set of results from the study which demonstrates the amount of plastic that was extracted from the soil samples during each un-burial. Very little fragmentation occurred from the samples that were initially left untreated or oven-treated before burial. UV-treated samples showed far greater fragmentation to the point where after 82 months (seven years) very few of the particles could be successfully extracted from the soil. The samples had evidently fragmented to such an extent that they were almost impossible to remove from the surrounding soil. However, Briassoulis found that under a microscope many fragments were still apparent (as seen in Figure 16). It is therefore impossible to quantify the amount of biodegradation (if any) that occurred during the experimentation period—this typifying one of the limitations of real field testing. The results in Figure 15 would therefore represent the absolute upper boundary for possible biodegradation for each sample; for the UV treated sample this therefore represents something less than 6.3% after 19 months, and something less than 89% after 82 months.

The issue of significant accumulation in the soils of microplastics is raised by the author as an important potential issue. As microplastics were clearly identifiable after seven years, there may be an even greater accumulation if the soil is reworked and replanted every year. There is no hypothesis presented in the study with regard to whether this process would increase fragmentation or what kinds of effect it would have on soil and crops. Furthermore, it is by no means certain that such microplastics would remain immobile within the soil. On the contrary, it is quite possible that plastic fragments may be mobilised by water or become airborne, and there could be a transfer to other environments such as rivers and oceans.

Figure 16: UV treated Samples after 82 Months



Source: Briassoulis (2015)

In 2009 Husarova[89] performed soil and composting degradation tests on two pre-treated LDPE films both containing Add-X's AddiFlex pro-oxidant additive fragmented to below 2mm, with one of the samples also containing calcium carbonate as a filler. The samples were pre-treated at either 40 or 80°C for 28 days in order to ascertain whether this would produce any difference during the biotic stage of degradation. In the simulated soil environment, this was found to be the case, although after 460 days only 16% had biodegraded after 80°C pre-treatment, and 13% after 40°C pre-treatment. In these soil environment tests, degradation was found to be more pronounced in the sample containing the calcium carbonate filler suggesting that this increased the bioavailability of biodegradable compounds.

The standard test method used in the French standard AC T51-808 (as detailed in Section 3.4) uses an entirely different approach to measuring and assessing both the abiotic and biotic stages of degradation:

1) **Abiotic test** – Using FTIR analysis to measure the absorbance at 1,714 cm^{-1};
2) **Biotic Test** – Using two ATP tests to determine bacterial sustenance:
    a. ATP level in cells with polymer should stabilise at a level 3 times higher than the control without polymer;
    b. ADP/ATP ratio ≤ 3.

The method has been pioneered by the Centre National D'evaluation De Photoprotection (CNEP) in France, advocating PAC plastics. A non-peer reviewed study[90] conducted by CNEP on behalf of Symphony used this test method to evaluate whether an LDPE film containing a 1% prodegradant additive can be certified according to AC T51-808. Although the CNEP study concludes with a positive certification of the Symphony PAC plastic film, the

[89] Husarova, L., Machovsky, M., Gerych, P., Houser, J., and Koutny, M. (2010) Aerobic biodegradation of calcium carbonate filled polyethylene film containing pro-oxidant additives, *Polymer Degradation and Stability*, Vol.95, No.9, pp.1794–1799

[90] CNEP (2014) *Evaluation of the Oxobiodegradability of a LDPE Film Containing 1% DG 12.08 (R2014-222)*, Report for Symphony Environmental Ltd, May 2014

information presented within the test report either fundamentally confuses the ATP test with the ADP/ATP ratio test, or the data is simply not well presented enough to allow a proper interrogation.

Elsewhere it is argued that the ATP tests are not a conclusive indicator of biodegradability because:

1) The test gives no indication of the absolute amount of biodegradation that has taken place[91]; and
2) The ADP/ATP ratio of ≤3 which is used as the pass criteria for the test only represents minimal cell activity and therefore is not proof of biodegradation.[92]

In most cells ATP concentrations are 10 to 100 times that of ADP[93] (i.e. 0.1 to 0.01 expressed as an ADP/ATP ratio), therefore the threshold ratio of 3 is an order of magnitude above this.

In 2010 Fontanella[94] studied three types of PAC plastics in simulated composting and soil environments. Samples were pre-treated thermally and with UV light to simulate around three years of outdoor weathering before being introduced to the microbes. A standard CO_2 evolution test found that in soil, biodegradation was estimated at between 5% and 12% over the course of a year (see Figure 6 in Section 4.1.2). LDPE was found to degrade more than HPDE, and the control material cellulose degraded by 69%.

The ATP test was also introduced as a new method and therefore was not based on any standard test method, however it formed the foundation of the French standard T51-808. The results of this are shown for two different additives in Figure 17. A large variation is seen between materials for sample P1, with HDPE performing particular poorly. This was explained as a result of HDPE also failing to oxidise as well as LDPE or liner LDPE (LLDPE) during pre-treatment. This again, highlights the importance of pre-treatment conditions. In most cases the ATP level remained stable for 180 days which indicates that the bacteria were feeding from the samples. A third sample (P3) was also subjected to this test in which very low ATP concentrations were found and the bacteria subsequently failed a viability test (the bacteria died).

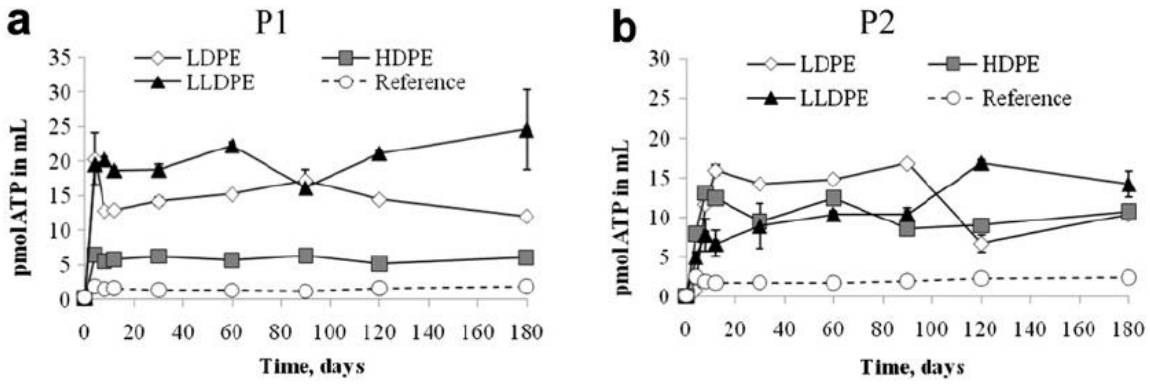
[91] Fontanella, S., Bonhomme, S., Koutny, M., et al. (2010) Comparison of the Biodegradability of Various Polyethylene Films Containing Pro-oxidant Additives, *Polymer Degradation and Stability*, Vol.95, No.6, pp.1011–1021

[92] Deconinck, and De Wilde, B. (2013) *Benefits and Challenges of Bio- and Oxy-degradable Plastics. A Comparative Literature Study*, Report for Plastics Europe, August 2013

[93] Karp, G.(2009) *Cell and Molecular Biology: Concepts and Experiments*, John Wiley & Sons (page 91)

[94] Fontanella, S., Bonhomme, S., Koutny, M., et al. (2010) Comparison of the Biodegradability of Various Polyethylene Films Containing Pro-oxidant Additives, *Polymer Degradation and Stability*, Vol.95, No.6, pp.1011–1021

Figure 17: ATP Tests for Two Prodegradant additives



Source: Fontanella (2010)

Table 5 shows the results of the ADP/ATP ratio test[95] for LLDPE with the P1 additive (the best performer) and HDPE with the P3 additive (the worst performer). This is compared with the results from the conventional CO_2 evolution test in soil. It demonstrates that although the ADP/ATP ratio for LLDPE is far below the ceiling of three required in the French standard, the level of observed mineralisation for the same material type over the course of a year is still very low. For HDPE the ADP/ATP ratio is high (signalling low bacterial activity), while the level of biodegradation under the mineralisation test is accordingly low. Again, this could also be attributed to the lower results achieved in the abiotic pre-treatment.

Table 5: ATP test results compared with biodegradation estimate

Material	ADP/ATP Ratio	Mineralisation after 352 days at 25°C in soil
LLDPE (P1)	0.3	12%
HDPE (P3)	5.8	<5%

In the concluding remarks, the paper states that:

> *"… it is not possible to make even a rough estimation of the process extent and eventually the time necessary for the ultimate biodegradation of the sample under applied laboratory conditions"*

Therefore, the tests conducted cannot predict how long a material will take to biodegrade in a simulated environment, and therefore even less so an open environment.

One final conclusion given by the paper is;

> *"…the most important parameter is the nature, the composition and the concentration of the metals present in the complexes used as prooxidant additives."*

[95] The lower the ratio, the higher the energetic state of the cells.

It highlighted that certain additives such as cobalt can inhibit bacteria growth so therefore it is clear that not all additive formulations are appropriate for use—sample P3 effectively killed the bacteria in the ATP test. This suggests that it is crucial that any plastic containing prodegradant additives must be subjected to standardised tests before entering the market.

A further test method[96] is currently being developed by Dr Ruth Rose of Queen Mary University of London on behalf of Symphony Environmental. In developing a new method, the French standard was evaluated which found that;

- The method for defining the number of bacteria cells used in the test was not defined;
- Sieving the plastic was required, but this proved impractical and could cause mechanical damage and therefore influence the results; and
- The ATP concentration was significantly lower than observed in Fontanella[97] due to cells adhering to the plastic making it difficult to remove them.

In this analysis it was concluded that the ATP test could potentially underestimate the ATP concentration for PAC plastic—i.e. show less bacterial activity than is actually occurring. The decision was therefore taken to use carbon dioxide evolution as the indicator of biodegradation. However, rather than using soil or compost samples with potentially unknown concentrations or types of bacteria (ASTM uses local soil samples in testing), specific bacteria are placed on the PAC plastic. This allows the activity of the bacteria to be isolated. The tests used LDPE samples that were artificially aged over different timescales by Symphony's in-house abiotic testing lab.

Although a full set of initial results were made available for this report, they cannot be published here before they are first published in a recognised journal[98] (journals insist on original content). The findings are significant and the test method unique enough that a general overview of the results is provided instead.

The new test method used specific bacteria r*hodococcus rhodochrous* (in the same way as the ATP test) rather than using soil samples which are difficult to control. Once these bacteria had adhered to the plastic it was very difficult to remove them for accurate analysis; therefore, CO_2 evolution was chosen as the preferred method. This means that the precise actions of the bacteria can be isolated and biodegradation over time can be directly measured—something that the ATP test cannot achieve.

Using this test on UV pre-treated PAC LDPE (with a molecular weight of <5,000), small levels of biodegradation were observed which if left to continue at the same rate would lead to full biodegradation in around 2 years. Conventional LDPE which had also undergone UV pre-treatment (but for twice as long) appeared to be susceptible to attack by the bacteria albeit at a smaller level equating to a biodegradation time of three years. This appears to occur despite the fact that the conventional LDPE was measured at higher molecular weight.

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[96] All information taken from personal communication with Dr Ruth Rose

[97] Fontanella, S., Bonhomme, S., Koutny, M., et al. (2010) Comparison of the Biodegradability of Various Polyethylene Films Containing Pro-oxidant Additives, *Polymer Degradation and Stability*, Vol.95, No.6, pp.1011–1021

[98] This is expected to happen towards the end of 2016.

This does correlate with Reddy's findings[99] which were detailed in Hypothesis 2. Reddy found that because molecular weight is a measure of the average across a sample there will be areas of much lower molecular weight. These lower areas are attacked first by the bacteria which actually results in the average molecular weight of the sample increasing. The same could be happening to the conventional plastic and is almost certainly happening in PAC plastic. UV ageing appears to have the same effect on both kinds of plastic, but the process is much more accelerated for PAC plastic.

It is, however, unclear how these results can be translated to behaviour in the real world. One strain of bacteria is used in the test whereas in the open environment there may be many more, as well as fungi which may also attack and break down the plastic—and therefore it may biodegrade quicker. However, some environments such as sandy deserts are known to have very little in the way of active bacteria and therefore biodegradation is unlikely to occur—this is particularly relevant in light of the UAE mandating that PAC plastic is required for all single use items.

With temperatures, UV, moisture levels and damage caused by mechanical action etc. in 'open environments' being so highly variable, there is no easy way of comparing simulated laboratory results to real world situations. Much of the literature and still emerging scientific results shows fragmentation and biodegradation of PAC plastic to occur under simulated conditions and/or in simulated environments, but there remains limited information to definitively conclude on what happens in the open environment. From the information studied, the authors of this report can believe that it is possible for a PAC plastic to fully mineralise in an open environment, with the prodegradant additives encouraging this action, and thus the polymers and entrained substances can be assimilated into the natural environment. Three crucial tests ought to be:

1) whether the PAC plastic product can fulfil its service life requirements without negative consequence; and
2) whether full biodegradation will happen in any real world situation within a reasonable time frame once released to the open environment; and
3) whether this should be expected from the products which are being placed on the market.

Producers of PAC plastics claim that they can engineer a product to meet the needs of the customer and the situation which the material may end up in if littered. There is a trade-off here as highlighted by Jakubowicz (2011) in the opening to its conclusions with *"Biodegradable polymers exhibit a delicate balance between the achievement of useful technological performance and rapid and effective biodegradability."* In simple terms products are adjusted through the use of greater or lesser prodegradant and anti-oxidant concentrations, although the physical dimensions of the product are likely also to be important. This then presents the problem that such tailored products will behave differently one from another in practice, and–with 'open environment' conditions being so variable and unpredictable–very little can be concluded concerning the actual behaviour of

[99] Reddy, M.M., Deighton, M., Gupta, R.K., Bhattacharya, S.N., and Parthasarathy, R. (2009) Biodegradation of Oxo-biodegradable Polyethylene, *Journal of Applied Polymer Science*, Vol.111, No.3, pp.1426–1432

PAC plastic products in the open environment. It is thus not possible to definitively conclude on the above questions, nor to give a decisive answer to the hypothesis overall.

Two further questions then follow, as linked to the previous ones:

4) whether [and how much] partly degraded plastic becomes mobilised during its degradation period; and
5) what environmental impacts can be expected.

Again these are challenging questions, and are a further focus for the hypotheses investigated under Section 4.2

4.1.3.1 Conclusion

Hypothesis 3: In open environments, PAC plastics biodegrade following their fragmentation.

Partially Supported.

A summary of the evidence can be found in Table 6.

One of the key findings of this report is that, without exception, the scientific evidence suggests that the conditions present during the abiotic stage (which in most studies is simulated by some form of accelerated pre-treatment) of degradation will have a significant impact on the materials' ability to subsequently biodegrade. Without this initial stage the PAC plastics will almost certainly fail to biodegrade in any meaningful way—the industry itself also confirm that this is the case and maintain that this is an important stage in the lifecycle of the product in making sure that the plastic does not degrade whilst it is still in use.

The ATP test is questionable in whether it truly suggests biodegradation is happening at an acceptable rate and, as a relatively new method in this context, it has yet to gain universal acceptance—only the French standard uses it at present. A new method currently in development by Queen Mary University develops upon the ATP test by maintaining the use of isolated bacteria types, but directly measuring the CO_2 evolution. It is therefore said to be possible to measure and track the level of biodegradation over time. This work is yet to be published, however, and whilst is does appear to directly indicate that bacteria can 'feed' on pre-treated PAC plastic, both the timescale until full biodegradation and how this might relate to real life in actual open environments is yet to be determined.

The best level of biodegradation extrapolated by Queen Mary University's work suggests that it would require over two years for PAC LDPE to biodegrade fully following a reduction in molecular weight to <5,000. This may be compared with the Jakubowicz 2011 soil burial tests of engineered short life PAC plastic, where 91% biodegradation was observed after two years following a simulated biotic oxidation period. This is the only peer reviewed study which has signalled a conclusive and positive result for biodegradability in soil, and 91% degradation at 733 days following pre-treatment has to be considered as the shortest observed, albeit not typical, timeframe in which a consistent degradation of one particular product took place in experimental conditions.

The important consideration is therefore determining whether this "shortest observed" timeframe (or any longer timeframe that may be anticipated for other products or for products in real life situations) is an acceptable period in which PAC plastic can remain in the

environment. It can be believed that degradation periods for PAC plastic can be much shorter than should be expected for degradation of conventional plastic, but consideration should be given to whether there are increased negative environmental impacts during this timeframe compared to counterfactual situations.

It is also problematic that no dedicated standards are currently in place that allow the PAC plastics industry to test and certify their products within Europe. In the same way that industrial composters require their feedstock to be EN 13432 compliant, customers of PAC plastic can have no confidence that they are making the right purchasing decision in the absence of certification on products. At present any purchasing decision is mired in controversy and confusing information from different sources.

Table 6: Studies Testing the Biodegradability of PAC Plastics in Conditions Intended to Simulate the Open Environment

This summary table uses a crude colour grading system to indicate certain methodological strengths and weaknesses; from green to red indicating favoured to less-favoured.

Author	Peer Review	Additive (Supplier)	Pre-treatment	Number of Reps	Degradation	Status at end of test	Time
Laboratory with Ambient Temperature Soil (~23°C)							
Husarova (2009)	Yes	AddiFlex (Add-X Biotech)	40—80 days @ 70°C	3	13—16%	Stopped Degrading	460 days
Feuilloley (2005)	Yes	Actimais (Trioplast)	None	1	1.8%	-	84 days
Chiellini (2003)	Yes	TDPA (EPI Environment)	44 days @ 55°C	3	49 – 63%	Slowly Increasing	600 days
Jakubowicz (2011)	Yes	P-Life (P-Life Japan)	10 days @ 65°C	3	91%	Slowly Increasing	733 days
Jakubowicz (2003)	Yes	EKM	28 days @ 70°C	1	60—65% (@ 60°C)	Stopped Degrading	200 days
CNEP (2014)	No	D2w(Symphony)	17 days @ 60°C	3	Pass AC T51-808	Unknown	120 days
Field Tests							
Fontanella (2010)	Yes	Not Specified	3 years outdoor	3	5 – 12%	Stopped Degrading	325 days
Briassoulis (2014)	Yes	Envirocare AG1000 (Ciba)	3 months outdoor	3	none	Film still intact	8.5 years
Briassoulis (2015)	Yes	Envirocare AG1000 (Ciba)	None	3	none	Film still intact	7 years
Briassoulis (2015)	Yes	Envirocare AG1000 (Ciba)	33 days UV @ 50°C	3	Fragmented	Fragmented <0.5mm	7 years
Briassoulis (2015)	Yes	Envirocare AG1000 (Ciba)	33 days no UV @ 50°C	3	Fragmented	Fragmented	7 years
Michigan University (2015)	Yes	Reverte (Wells Plastics Ltd), d2w (Symphony)	None	4 each	negligible	-	1095 days

4.1.4 Hypothesis 4: PAC plastics do not biodegrade in landfill.

The landfill environment is characterised by being an anaerobic process i.e. reactions occur that do not require oxygen as a catalyst. However, this is only after the material has been covered up significantly. Before that point, and when the material has access to air it can degrade aerobically. The key distinction from an environmental protection point of view is that aerobic degradation produces CO_2 whereas anaerobic degradation produces methane—a greenhouse gas 25 times more harmful (on a 100 years' time horizon) than CO_2. Although part of methane is captured by gas wells and subsequently degraded to CO_2 by flaring systems, a large part of it is released as a fugitive gas into the atmosphere, hence it contributes to the global warming effect. It is th erefore important to ascertain whether PAC plastic can degrade anaerobically in landfill.

The benefits of PAC plastic in the landfill context have often been extolled. In a discussion piece by Wiles and Scott[100] (Scott is widely believed to be the inventor of PAC plastic) the use of PAC plastic as bin liners can provide a useful function by fragmenting and therefore allowing its contents to mix and settle easier. The use of PAC plastic as a daily landfill cover under the brand Envirocover[101] from EPI is also suggested as a good and cost effective alternative to soil. Again, its ability to fragment is the key selling point.

It is also suggested[102] that even materials that are anaerobically biodegradable such as paper may not fully biodegrade in a deep landfill due to the cold, dry environment. However, *abiotic degradation*—observed by a reduction in elongation at break after 98 days— of PAC plastic can still occur at depths of 2 meters.[103]

Very few recent studies are available on the subject of biodegradation of PAC plastic in landfill. This is possibly due to the less contentious nature of the issue—i.e. different materials already either biodegrade or are inert in landfill, therefore whichever behaviour PAC plastic takes is unlikely to change how we view and manage landfill.

Since deep landfill is known to contain very little oxygen, much of the biodegradation takes place anaerobically. In 2007 California University[104] looked at a number of materials in different environments (the study is also cited in other hypotheses within this current report). One of these environments was anaerobic digestion (AD). Whilst this is not an accurate portrayal of landfill conditions, the process is *anaerobic* and therefore gives a good indication of how PAC plastic may behave in this environment. In this case no biodegradation was measured over 43 days whereas 6% biodegradation was observed for paper. This is obviously a very short period of time when compared to landfills that are expected to last for many years.

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[100] Wiles, D.M., and Scott, G. (2006) Polyolefins with Controlled Environmental Degradability, *Polymer Degradation and Stability*, Vol.91, No.7, pp.1581–1592

[101] http://www.envirocoversystem.com/

[102] Billingham et al (2000) Controlled – Lifetime Environmentally Degradable Plastics Based on Conventional Polymers, paper given at Addcom World 2000, Switzerland, 2000

[103] ibid

[104] California State University (2007) *Performance Evaluation of Environmentally Degradable Plastic Packaging and Disposable Food Service Ware - Final Report*, Report for California Integrated Waste Management Board, June 2007

A recent study from the Czech Republic[105] attempted to test for biodegradation in landfill of various plastic and non-plastic carrier bag materials that are marketed as biodegradable or oxo-biodegradable. The samples were inserted into a working landfill using a recoverable cage and left for one year. After this time, the materials were excavated and examined. All of the plastic materials including a PAC plastic with TDPA additive showed no signs of disintegration or even a significant change in the colour printing on the outside of the bag. The control—cellulose—displayed almost complete biodegradation in that time which demonstrated that the conditions were suitable and representative.

4.1.4.1 Conclusion

Hypothesis 4: PAC plastics do not biodegrade in landfill.
Supported. The evidence supports the hypothesis.
The issue of whether PAC plastic degrades in landfill is not as straightforward as some of the other environments. In this case, as a semi-managed environment there are controls in place, however there is also a lot that is not fully understood about how individual materials behave within a landfill. Whilst PAC plastic may biodegrade in the upper levels of a landfill in aerobic conditions (see hypotheses 2 and 3) and therefore produce CO_2, it has already been demonstrated that this happens at a very slow rate, and only if abiotic degradation has already occurred. The limited evidence that is available suggests that deeper in landfill under anaerobic conditions there will be little or no biodegradation taking place. In this case, the carbon is effectively sequestered, avoiding the direct release of GHGs to the atmosphere.

[105] Dana Adamcová, and Magdalena Vaverková (2014) Degradation of Biodegradable/Degradable Plastics in Municipal Solid-Waste Landfill, *Pol. J. Environ. Stud*, Vol.23, No.4

4.1.5 Hypothesis 5: PAC plastics biodegrade in marine environments.

Although this hypothesis is aimed at the biodegradability of oxo-degradable plastic in marine environments—specifically marine water—the evidence for degradation in fresh water will also be investigated. As is discussed further in Hypothesis 7, rivers are one of the key transport mechanisms for microplastics into the oceans, and therefore it is also important to consider how PAC plastic might behaves once entered into these environments.

As part of an evidence review for UNEP[106] Dr Peter Kershaw concluded that;

> *"The fate of these fragments (microplastics) is unclear, but it should be assumed that oxo-degradable polymers will add to the quantity of microplastics in the oceans, until overwhelming independent evidence suggests otherwise."*

Kershaw also suggested that PAC plastic can persist for 2 to 5 years in the marine environment leading to undesirable impacts.

Scientifically, there has been far less focus on these environments until recently because:

- Only in the last decade has plastic pollution in the marine environment become an important and mainstream issue;
- The marine environment is diverse and includes many sub-environments such as beaches and sediments as well as differing depths of water;
- It is much more difficult to study and replicate tests; and consequently
- There are very few national and international standards that cover the behaviour of material in aquatic environments.

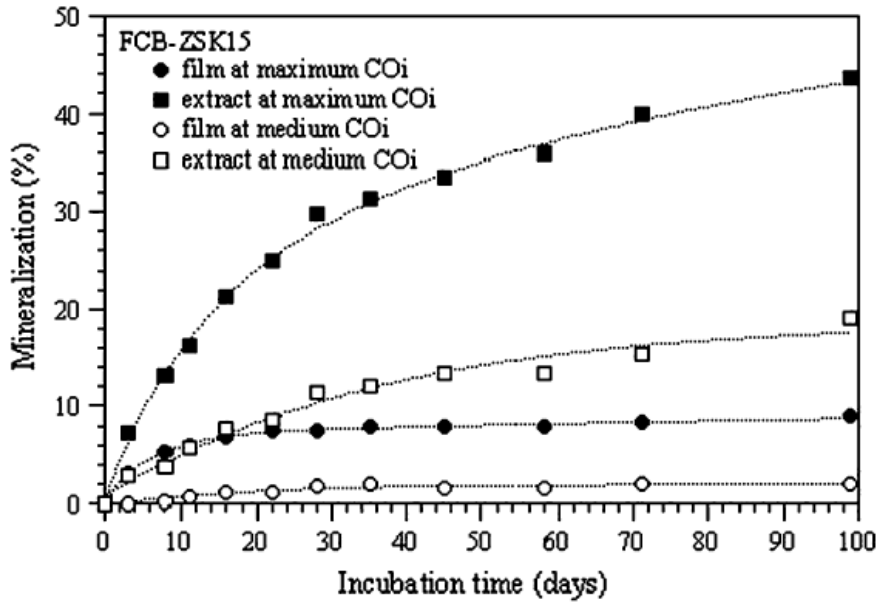
This means that the body of evidence is not as comprehensive as compared to that related to compost and soil, and the test methods can differ greatly. The following is an overview of the scientific evidence with regard to biodegradability of PAC plastic in the marine environment.

Chiellini, who had previously studied the biodegradability of PAC plastic in soil and compost, conducted a study[107] in 2006 which looked at the degradability of the same material – TDPA, from EPI Environment – in fresh water. The plastic material was tested in two forms, containing either 10% or 15% pro-oxidant additive. After 100 days of incubation, the material containing the highest level of additive degraded by around 10%, as seen in Figure 18. Higher degradation rates of up to 40% were, however, achieved using extracts of oxidised polymer with a low molecular weight compared to the complete film.

[106] Kershaw, D.P.J. (2015) *Biodegradable Plastics and Marine Litter. Misconceptions, Concerns and Impacts on Marine Environments*, Report for United Nations Environment Programme (UNEP), November 2015

[107] Chiellini, E., Corti, A., D'Antone, S., and Baciu, R. (2006) Oxo-biodegradable Carbon Backbone Polymers – Oxidative Degradation of Polyethylene under Accelerated Test Conditions, *Polymer Degradation and Stability*, Vol.91, No.11, pp.2739–2747

Figure 18: Mineralisation of PAC Test Samples in Fresh Water



Source: Chiellini (2006)

In 2007, California State University,[108] on behalf of California's Integrated Waste Management Board conducted bio-degradation tests on a range of bio-based materials in marine water without applying any sort of pre-treatment. It tested plastic film containing EPI's TDNA – the same additive used in the Chiellini experiments, although the additive concentration is not disclosed.

Sample material was tested for biodegradation in marine water using ASTM D6691[109]. This is a test method for determining aerobic biodegradation of plastic materials in the marine environment. The test method is said to demonstrate satisfactory degradation if, after 12 weeks (84 days), at least 70 per cent of the material disintegrates. After 60 days the test found that the PAC material experienced no signs of disintegration. This was similar to all the other materials on study apart from one type of bio-based PHA, which degraded by over 60%. Further tests were also conducted with the PAC material by introducing UV light and heating up to 35°C for 14 days during submersion in sea water (i.e. a simulated accelerated aging). No weight loss was observed after that time, but the samples became brittle and several of the samples could be pulled apart and broken; this was considered to be due to polymer chain scission caused by the UV light, i.e. part of the abiotic degradation processes. The study concludes that more work is necessary to understand how these plastics break down in the marine environment.

The results of the test are perhaps not surprising given that the PAC plastic was not subjected to any kind of [accelerated] abiotic pre-treatment. As has been confirmed from

[108] California State University (2007) *Performance Evaluation of Environmentally Degradable Plastic Packaging and Disposable Food Service Ware - Final Report*, Report for California Integrated Waste Management Board, June 2007

[109] ASTM D6691: Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials in the Marine Environment by a Defined Microbial Consortium or Natural Sea Water Inoculum

the investigation into soil and composting environments, the incorporated anti-oxidant package helps to slow the abiotic degradation to lower molecular weight polymer chains, which would then be more readily bio-available for biotic degradation. Without significant reduction in molecular weight, which is unlikely to have occurred in these tests, PAC plastic is not expected to biodegrade. Furthermore, sea water is a much less aggressive environment for biodegradation.

In order to investigate the potential consequences of PAC plastic becoming marine debris, in 2012, Müller et al[110] used the gastrointestinal fluids of sea turtles to study whether three kinds of typical shopping bag material would degrade: conventional HDPE; bio-based; and PAC polyethylene with d2w additive, from Symphony Environmental. All plastics were sourced from supermarket bags available in Australia. Again, no pre-treatment was used to simulate the abiotic phase (except for the time spent between manufacture and retrieval from the supermarket). As well as testing each material in triplicate in the gastrointestinal fluids, both salt and fresh water controls were also used.

The degradation rate was measured over 49 days, but showed no significant change in mass for either the PAC or conventional plastic in any of the test environments. The bio-based plastic showed a decrease in mass of between 3 and 9 per cent—however it was noted that this is considerably less than other studies have shown over the same period in environments such as industrial composting.

Along with the soil bacteria tests conducted by Queen Mary University (see Hypothesis 2) the same tests were also undertaken using bacteria from the marine environment—*A. borkumensis.* Again, we are not at liberty to publish full results but have been permitted to present a summary of the findings to date.

The results are very similar to those which were observed for the soil samples. It demonstrates that marine bacteria are just as capable of biodegrading the PAC plastic as soil bacteria. Both the tests for soil and marine bacteria were carried out using the same concentrations of bacteria on the samples. This allows direct comparisons to be made. In this, case it is clear there is very little difference between the bacteria in terms of their ability to feed on the plastic. In terms of translating these results to real life, this is even more fraught with difficulty for the marine environment. Directly comparing bacteria at the same concentration may be sufficient for the laboratory: however these bacteria are likely to be present in far lower concentrations in the marine environment than they are in the soil. Other factors aside, one would therefore expect the biodegradation process to proceed more slowly in the marine environment, especially without the presence of other aggressive attacks from fungi. The hydraulic action of the sea may also be relevant; for instance, once the plastic is abiotically degraded and brittle, it might be expected that this would encourage fragmentation.

Further tests have also been carried out by Queen Mary University on samples that have been aged naturally. These samples were the products of the aging experiment that was

[110] Müller, C., Townsend, K., and Matschullat, J. (2012) Experimental Degradation of Plymer Shopping Bags (Standard and Degradable Plastic, and Biodegradable) in the Gastrointestinal Fluids of Sea Turtles, *Science of The Total Environment*, Vol.416, pp.464–467

conducted by SEVAR[111] on behalf of Symphony (detailed in Hypothesis 1). The particular samples taken forward for biodegradation experiments were aged under 40cm of sea water for 60 months which resulted in a molecular weight of 14,000 for PAC LDPE, and 75,000 for conventional LDPE. During the biodegradation tests, PAC plastic was then found to degrade more than the conventional plastic.

These findings suggest that during pre-ageing under water, PAC plastic is much more susceptible to UV degradation than conventional plastic (as demonstrated by the large difference in molecular weight). The biodegradation tests also indicate that bacteria can feed off plastic measured with a higher molecular weight than the 5,000 limit often used to characterise this. It is important to recognise, however, that molecular weight figures are an average across the sample, therefore there will be areas of the plastic that are above the measured value and areas that are below (i.e. potentially below <5,000).

Early indications from the ongoing Queen Mary University studies suggest that biodegradation using marine bacteria takes considerably longer than is the case for soil bacteria—even in the few experiments that showed a consistent degradation. It should also be understood that these tests are conducted with equivalent concentrations of marine and terrestrial bacteria. On the assumption that the availability and concentration of bacteria in land environments is much greater than for marine environments, biodegradation of PAC plastic in a true marine environment can be expected to be further considerably impeded. It must be stressed that these theories are based on preliminary tests only, and further analysis is required when the tests have been completed. Nevertheless, as one would expect from the hierarchy of aggressive environments presented in Figure 1 on page 6, there is a clear indication that marine biodegradation will happen at a much slower rate than soil degradation – if it is to occur at all in practice.

From the limited evidence available, it can be believed that abiotic degradation and fragmentation of PAC plastics can occur in marine environments, even if this may be reduced compared to land based environments. However, whether biodegradation can be expected to occur in any acceptable timescale, if at all, is far from certain.

This therefore leaves similar environmental concerns as with conventional plastic in marine environments, but with PAC plastic having a potential increased propensity to fragment to microplastic debris. Further discussion on this is undertaken in Hypothesis 7.

4.1.5.1 Conclusion

Hypothesis 5: PAC plastics biodegrade in marine environments.
Inconclusive. There is partial evidence to support, there is partial evidence to refute.
A summary of the evidence can be found in Table 7. Currently there is insufficient evidence showing biodegradation of PAC plastic in the marine environment. There is some evidence from a few trials that certain bacteria found

[111] SEVAR *Response of Polyethylene Films Containing Oxo-additive, When Submitted to Wet Environment (Sea and Fresh Water)*, Report for Symphony Environmental Ltd

in marine waters can attack and consume PAC plastic so long as it has been sufficiently abiotically degraded beforehand. However, this process appears to occur at a considerably slower pace than in similar tests run in soil, and the low concentration of bacteria in marine environments casts additional doubt on whether biodegradation may occur in real life situations to any meaningful degree.

Very little testing has been undertaken and there are currently no standards that can be met that will allow a certification. The replication of marine environments for laboratory testing is fraught with difficulty—something which also impacts bio-based plastics. If any such standard were to be developed, it should be enforced that any 'marine degradable' certification should not be used for marketing purposes (i.e. as a selling point) to avoid any potential weakening efforts made on litter prevention in practice.

The timeframes and expected impacts are particularly important to consider for the marine environment. The evidence suggests that PAC plastic in aqueous environments can experience polymer chain scission to lower molecular weights over and above that for conventional plastic, thus encouraging fragmentation to microplastics. But with much slower biodegradation expected in water compared to land based open environments, this presents serious environmental concerns.

In soil, a conclusion was given in the literature that *"…it is possible to create LDPE-based materials that will almost completely biodegrade in soil within two years. It also indicates that the risk of plastic fragments remaining in soil indefinitely is very low."* [112] No such assurances can be made for PAC plastic in marine environments. This highlights the concern that plastic fragments may be generated and remain either indefinitely, or for long enough to cause significant environmental damage. Such issues are considered further within Hypothesis 7.

[112] Jakubowicz, I., Yarahmadi, N., and Arthurson, V. (2011) Kinetics of Abiotic and Biotic Degradability of Low-density Polyethylene Containing Prodegradant Additives and its Effect on the Growth of Microbial Communities, *Polymer Degradation and Stability*, Vol.96, No.5, pp.919–928

Table 7: Studies Testing the Biodegradability of PAC Plastics in the Marine and Fresh Water Environments

This summary table uses a crude colour grading system to indicate certain methodological strengths and weaknesses; from green to red indicating favoured to less-favoured.

Author	Peer Review	Additive (Supplier)	Pre-treatment	Number of Reps	Degradation	Status at end of test	Time
Seawater							
California University (2007)	No	TDPA (EPI Environment)	None	2	None	-	60 Days
Müller (2012)	Yes	d2w (Symphony)	None	3	Negligible	-	49 days
Fresh Water							
Chiellini (2007)	Yes	TDPA (EPI Environment)	25 days @ 70°C	3	10%	Slowly Increasing	100 days
Müller (2012)	Yes	d2w (Symphony)	None	3	Negligible	-	49 days
Marine Animals							
Müller (2012)	Yes	d2w (Symphony)	None	3	Negligible	-	49 days

4.2 Issues of Littering

4.2.1 Hypothesis 6: In soil, fragmented and potentially partially degraded plastics and their additives pose no negative effects to soil quality or ecosystems.

The issues surrounding the toxicity of the materials and chemicals used in the production of PAC plastic have been the focus of some debate in recent years. This has usually focused on two specific questions:

- Do the additives contain heavy metals or other toxic substances? And
- Will these substances cause any direct harm if the product breaks down in soils?

The main substances used to produce the additives are salts of manganese, iron or cobalt.[113] Cobalt was already highlighted as a substance of concern in Section 4.1.3, where Fontanella[114] found that high levels of cobalt in one of the additives used in study contributed to the failure of the bacteria viability test—i.e. it killed the bacteria. The OPA state that this additive is used for transparent plastic only,[115] although a recent conference paper[116] suggests that cobalt can be used as an additive to initiate the oxidative degradation of HDPE when it is initiated by heating compared with the usual mechanism of UV light—it therefore appears to have applications beyond transparent plastic.

Due to the concerns over toxicity, BS 8472 (UK), ASTM D6954 (USA) and SPCR 141 (Sweden) all include some form of toxicity test or heavy metal limit that the sample must pass. Notably, however, the two best known standards that provide actual certification criteria—AC T51-808 (France) and S5009 (UAE)—do not specify any form of toxicity test (see Table 2 in Section 3.4) although the ATP test used in AC T51-808 assumes that if the bacteria are still active on the sample, then they have not been adversely affected by the material or its additives.

Most standards specify a minimum of a plant germination test using OECD 208.[117] This test guideline is designed to assess effects on seedling emergence following exposure to the test substance applied to the soil surface or into the soil. Only SPCR 141 specifies a target for this test of 90% germination compared with a control sample. Other standards do not specify a target. Some standards also specify an earthworm toxicity test (OECD 207[118]), but again, no targets are given.

S5009 specifies limits for the maximum concentration of metals in the final untreated PAC plastic material—including cobalt. The reasons for the choice of these limits is unclear as

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[113] Personal communication with Michael Stephen, OPA

[114] Fontanella, S., Bonhomme, S., Koutny, M., et al. (2010) Comparison of the Biodegradability of Various Polyethylene Films Containing Pro-oxidant Additives, *Polymer Degradation and Stability*, Vol.95, No.6, pp.1011–1021

[115] Ibid

[116] Asriza, R.O., and Arcana, I.M. (2015) Synthesis of Cobalt Stearate as Oxidant Additive for Oxo-Biodegradable Polyethylene, paper given at THE 5TH INTERNATIONAL CONFERENCE ON MATHEMATICS AND NATURAL SCIENCES, 30 September 2015, http://scitation.aip.org/content/aip/proceeding/aipcp/10.1063/1.4930711

[117] Test No. 208: Terrestrial Plant Test: Seedling Emergence and Seedling Growth Test

[118] Test No. 207: Earthworm, Acute Toxicity Tests

there is no documentation provided with the standard that supports any of the limit decisions. Nevertheless, testing has been undertaken by Intertek[119] on LDPE containing an additive from Symphony, which found that the plastic contained levels far below the limits specified.

Ecotoxicity tests have also been conducted on Wells Plastics' Reverte product by Biosystems Altanta. Both the worm and germination tests specified in ASTM D6954 were carried out for HDPE[120] and LDPE.[121] Earthworm survival was found to be 90% of the control sample for LDPE, and 100% for HDPE, whilst close to 100% was achieved for the germination tests of both materials. Whilst 90% is an acceptable earthworm survival rate, it is on the limit of what may be deemed acceptable and all three replications of the test for LDPE came up with the same result. This suggests that there are small negative toxic effects on the earthworms in this case.

It appears, therefore, that whilst there are test standards available for the toxicity of PAC plastic, very few specify targets to be achieved, and those that do provide little justification for these. The test reports made available for this study indicate that the toxic effects are small from PAC plastic.

A further potential issue is that of the build-up of microplastics in the soils caused by mulch films that have not degraded sufficiently between crop cycles. As already identified in the studies by Briassoulis[122] and Kyrikou[123], PAC plastic mulch films were found to have degraded very little over the course of seven years of partial burial after the initial crop cultivation period. Feuilloley[124] found that samples of soil taken from fields that had been cultivated using PAC plastic mulch films two years previously contained significant amounts of microplastics. It is unlikely that plastic carrier bag litter (for instance) could lead to such significant build-ups in soil, however, as they are not applied directly to soil in the same way as mulch films, nor in as high concentrations. We are able to conclude upon the impacts associated with plastic fragments in terrestrial environments, but these are likely to focus on concerns relating to direct ingestion or mobilisation and transport to marine environments.

Concerns relating to the use of stabilisers (i.e. anti-oxidants) are not widely covered in the literature. Stabilisers are added together with the pro-oxidant additives into PAC plastic. We have come across limited information on the types of stabilisers which are used (or have

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[119] Intertek (2013) *Characterisation of LDPE Polyethylene Film With 1% 93224/C ESMA 20213 Additive*, Report for Symphony Environmental Ltd, 2013

[120] Report No. 795 11046-1 -T3 from Biosystems Atlanta to Wells Plastics on ecotoxicity testing of partially degraded commercial HDPE film according to the ecotoxicity requirements of tiers 2 and 3 of ASTM6954.

[121] Report No. 795 11058-1 -T3 from Biosystems Atlanta to Wells Plastics on ecotoxicity testing of partially degraded commercial LDPE film according to the ecotoxicity requirements of tiers 2 and 3 of ASTM6954

[122] Briassoulis, D., Miltiadis Hiskakis, Epifaneia Babou, and Ioanna Kyrikou (2014) Analysis of Long-term Degradation Behaviour of Polyethylene Mulching Films with Pro-oxidants under Real Cultivation and Soil Burial Conditions, *Environmental Science and Pollution Research*, Vol.22, No.4, pp.2584–2598

[123] Kyrikou, I., Briassoulis, D., Hiskakis, M., and Babou, E. (2011) Analysis of Photo-chemical Degradation Behaviour of Polyethylene Mulching Film with Pro-oxidants, *Polymer Degradation and Stability*, Vol.96, pp.2237–2252

[124] Feuilloley, P., César, G., Benguigui, L., et al. (2005) Degradation of Polyethylene Designed for Agricultural Purposes, *Journal of Polymers and the Environment*, Vol.13, No.4, pp.349–355

historically been used) in PAC plastic. The press reports on health concerns associated with plastic additives generally, one recent example being bisphenol A (BPA) - a chemical that has been used to harden plastics for more than 40 years but for which increasing evidence on health effects has only recently emerged. A study from 2010 also highlights that chemicals with unknown toxicity can form when polypropylene plastic is heated in the manufacturing process.[125] Taking another example, acetaldehyde (a compound associated with a cancer risk) is also known to form during the thermal degradation of polymers including PET. Concerns over secondary chemicals come to the fore in the context of chemical migration from plastic packaging to contents, which has been shown to occur in numerous studies.

Although these concerns do not properly inform the discussion on whether PAC plastic itself may lead to health risks over and above those inherent to the use of conventional plastic, the fact that additional additives are used is of relevance. Additives associated with PAC plastic risk adding to the complexity of possible impacts and health concerns from plastic – whether this be directly from the pro-oxidant additives or stabilisers themselves, or whether from supplementary additives that may subsequently be added to recyclate as a mitigation measure for the inclusion of PAC plastic, or whether from secondary chemicals which may be formed from the breakdown of any of the primary additives. The science and evidence base within the field of toxicology is inherently under-informed. Since the use of plastic additives of all forms continues to change over time, toxicological knowledge is - at best - playing catch up to the developments in product manufacture. A precautionary view would therefore see merit in an approach to product engineering which avoids use of further additives and potential secondary chemicals about which long term chemical behaviour and associated toxicological implications are not known with certainty.

4.2.1.1 Conclusion

Hypothesis 6: In soil, fragmented and potentially partially degraded plastics and their additives pose no negative effects to soil quality or ecosystems.
Inconclusive. Although it may be possible to avoid negative effects, the evidence is insufficient to support the hypothesis and the lack of industry regulation gives cause for concern.
There appears to be very limited evidence in support of the view that *toxic heavy metals* are frequently used as an additive in PAC plastic, and that these can have harmful effects in soil. Other effects from the additives that may appear in these products are less clear. The use of cobalt has been observed by some studies, and in one case, this has been shown to have a significant negative effect on bacterial growth. This not only suggests that the material could be harmful, but it also makes it less likely to biodegrade. Industry consultation suggests the use of cobalt is not widespread, and is generally used in small enough quantities that it does not become an issue. Nevertheless, the possibility remains

[125] Reingruber, E., Himmelsbach, M., Sauer, C., and Buchberger, W. (2010) Identification of Degradation Products of Antioxidants in Polyolefins by Liquid Chromatography Combined with Atmospheric Pressure Photoionisation Mass Spectrometry, *Polymer Degradation and Stability*, Vol.95, No.5, pp.740–745

that producers can incorporate cobalt, or manganese, or other substances of concern, into their additives with no regulation to prevent this.

Most current test standards for PAC plastic do test for ecotoxicity and therefore those toxic effects being tested for will be highlighted if a product is put through one of these tests. There are very few targets, however, so the results are currently for information rather than as a way of conforming to a standard. The exclusion of any form of toxicity test in the UAE standard does mean that the products that end up on their market may not have demonstrated that they do not pose any significant harm. The same danger also exists in the EU where no regulation exists on these products, and agreement on what may be acceptable has yet to be decided.

Whilst it is outside of the scope of this report to analyse the issue of mulch films in great detail, it is also a concern that the build-up of plastic particles in agricultural soil could be an issue. Again, there are no controls over which PAC plastic products can be used in this environment and whether they are suitable for the purpose. Some may fragment and biodegrade sufficiently (although this is yet to be conclusively proven), but others may not, and it is very difficult to differentiate between the two and to understand the possible toxicological effects without a process of testing and validation.

4.2.2 Hypothesis 7: The use of PAC plastic does not instil or promote a throwaway attitude.

There has long been concern that littering may be increased where a product claims to be degradable in the environment, because of the assumption that some or all of the impacts of littering are therefore avoided. An analysis of environmental behaviour models found that the lower the perception of responsibility and capability to address an issue, the less likely a person is to take action.[126] This might suggest that the (suggested) provision of a technological fix to littering could reduce the public's perception of personal responsibility.

A report into the environmental impacts of PAC carrier bags asked major retailers in the UK whether they had any feedback from customers or others regarding PAC plastics with regard to littering.[127] Most retailers did not have information to contribute in this regard. One cited concerns that PAC bags "*can 'greenwash' consumers into believing that not re-using carrier bags is acceptable*." However no supporting evidence was provided.

Of the other stakeholders interviewed (environmental regulators, agricultural associations and recyclers), there was concern from the association for Organics Recycling (formerly The Composting Association) about householders using non-compostable bags as food bin liners, and efforts were being made to educate householders about this. However what effect labelling plastic bags in different ways (e.g. degradable, oxo-degradable etc.) actually had on householders was not demonstrated.

The report concluded:

> *"There was not found to be any robust evidence that the type of carrier bag affects the way in which they are disposed of by the public."*

However, there was no robust evidence that the type of carrier bag *did not* affect disposal by the public either: rather, the evidence was not persuasive of either view.

Vinçotte, which runs one of Europe's best known biodegradation labelling schemes, specifically forbids[128] communication of any certification gained under its 'OK biodegradable Marine' scheme. Only for products where marine biodegradability provides 'added value', such as a fishing line, can this certification be promoted. Other products that may be frequently littered cannot, so that "…it does not encourage littering." For similar reasons, both its soil and fresh water, marks can only be displayed on products that have a function in the same environment that they are required to biodegrade. These measures may in part be to avoid negative publicity from products bearing the Vinçotte mark being littered, but they may also be to prevent branding on products which itself might elicit littering.

Focus groups in Scotland showed that most participants felt that it was acceptable to litter biodegradable items as these were seen as harmless – though participants probably had

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[126] Klöckner, C.A. (2013) A Comprehensive Model of the Psychology of Environmental Behaviour—A Meta-Analysis, *Global Environmental Change*, Vol.23, No.5, pp.1028–1038

[127] Loughborough University (2010) *Assessing the Environmental Impacts of Oxo-degradable Plastics Across Their Life Cycle*, Report for Defra, January 2010

[128] Vinçotte (2015) *Bio Products - Degradation in Seawater*, 2015, http://www.okcompost.be/data/pdf-document/Program_OK_12e_a_OK_biodegradable_MARINE.pdf

food items in mind as it was thought that 'biodegradable litter' could even benefit wildlife.[129] Respondents to a survey (rather than the focus group) issued for the same study showed that 19% of them felt it was understandable to litter if the item was biodegradable or could rot away. In the US, young people interviewed also reported a greater inclination to litter when the item in question is biodegradable, and one group thought it was a commonly held view that cigarette butts were seen as biodegradable and acceptable as a form of litter.[130] Another survey on the reasons why smokers litter cigarette butts, documented that some respondents believed that cigarette butts are different to other types of litter, for reasons including that it was believed that cigarette butts are biodegradable.[131]
A more recent focus group revealed similar responses and states that [132]

> *"For some participants, the idea of 'degradability' makes litter [of fruit cores and skins] feel less unacceptable; a few people also mentioned this characteristic in relation to plastic bags or paper."*

In terms of what litter should be prioritized for clean-up,

> *"there was usually consensus about fast food packaging and associated plastic bottles and cans (high-ish or middling priority) and, as mentioned above, a low priority for fruit debris, and sometimes other biodegradable (or perceived to be) items (e.g. paper but occasionally also chewing gum and cigarette butts)"*

The report concluded that whether something is considered biodegradable was a "consistent criterion" for prioritizing litter clear-up.

In response to the question, "I'm more likely to litter when the item I'm holding is biodegradable", 22.6% of the respondents agreed or strongly agreed, while the remainder, 77.4% disagreed or strongly disagreed. Those who agreed to any extent scored more highly with regard to self-reported littering behaviour, suggesting that perhaps the propensity for biodegradable litter to promote littering behaviour is greater amongst those that are already more likely to litter.

The caveat to any survey or focus group based study is that reported 'hypothetical' behaviour is difficult to correlate with actual behaviour, for which empirical observations are necessary.

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[129] Keep Scotland Beautiful (2007) Public attitudes to litter and littering in Scotland, *cited in* Brook Lyndhurst (2013) *Rapid Evidence Review of Littering Behaviour and Anti-Litter Policies*, Report for Zero Waste Scotland, 2013, http://www.zerowastescotland.org.uk/sites/files/zws/Rapid%20Evidence%20Review%20of%20Littering%20Behaviour%20and%20Anti-Litter%20Policies.pdf

[130] S. Groner Associates (2009) *Littering and the iGeneration. City-Wide Intercept Study of Youth Litter Behavior in Los Angeles.*, Report for Keep Los Angeles Beautiful, 2009, http://www.cleanup-sa.co.za/images/Littering%20and%20the%20iGeneration_Youth%20Litter%20Study%20for%20KLAB%20.pdf

[131] ENCAMS (2008) *No Butts. Smoking-Related Litter*, 2008

[132] Brook Lyndhurst (2015) *Public Perceptions and Concerns around Litter*, Report for Zero Waste Scotland, 2015, http://www.zerowastescotland.org.uk/sites/files/zws/Litter%20Insights%20final%20web%20March%2015.pdf

An analysis of tobacco industry focus groups found evidence that tobacco companies thought that biodegradable filters might encourage littering.[133]

"A focus group participant wanted biodegradable filters because 'I want to just throw them down, but I don't want to feel bad about it'. Brown & Williamson concluded that the 'perceived benefit of a biodegradable filter' was 'the ability to litter without guilt'.

Because industry also thought that biodegradable filters 'may not degrade as quickly as smokers really want'; recognising that 'all discarded filter tips look alike to the public', an increased or static litter rate, and the fact that biodegradable filters would highlight the fact that the degradability of filters generally was an issue, would run counter the desire of industry to;

- stem the growing disapproval of smokers and of smoking;
- pre-empt environmental legislation by making regulation appear unnecessary;
- counter the negative publicity that the industry receives when litter surveys are published; and
- find a product feature that would offer a market lead i.e. competitive edge.

So this analysis believed that introducing biodegradable cigarette butts might either make the problem of littering worse, or, at least, no better and so provide no direct or knock-on economic benefit to them for the investment of introducing them.

However whether the belief around the increased or equivalent littering of biodegradable cigarette filters can be extended to other types of litter perceived as degradable is not known with certainty: cigarette butt litter is frequently perceived as in a different league to other types of litter such as bottles, cans or potentially bags of any type, because cigarette butt litter is relatively small and less conspicuous. The deliberate littering of plastic items—whether marked as biodegradable or compostable—may also have different connotations when compared to a fibrous product made from bio-based ingredients.

4.2.2.1 Conclusion

Hypothesis 7: The use of PAC plastic does not instil or promote a throwaway attitude.
Inconclusive. There is no evidence to support this hypothesis; there is partial evidence to refute the hypothesis.
Most of the relevant research conducted is based on self-reported behaviour from focus groups or interviews. Several such studies found that there was a significant proportion of respondents who thought they would be more likely to litter a biodegradable item, that littering biodegradable items was more acceptable, and that the clean-up of biodegradable items was less of a priority. In several cases however it was likely that the respondents had food items in mind when thinking of 'biodegradable' items, but there were some cases where plastic bags, chewing gum and cigarette filters were specifically mentioned. It is particularly interesting to examine the reasons why the tobacco industry

[133] Smith, E.A., and Novotny, T.E. (2011) Whose butt is it? tobacco industry research about smokers and cigarette butt waste, *Tobacco Control*, Vol.20, pp.i2–i9

has not supported biodegradable filters which is that available products do not degrade fast enough to improve their product image and achieve economic aims, exacerbated by the possibility that biodegradable filters would increase littering.

In order to prove or disprove this hypothesis conclusively, it is necessary to conduct empirical experiments that observe behaviour or quantify litter. For example, a test environment could be established where a known relative quantity of biodegradable and non-biodegradable items is distributed in various scenarios e.g. from a participating outlet or at an event and the amount of material littered of each type sampled. This should be conducted in a variety of circumstances, with different ways of signalling biodegradability (e.g. written on the bags, verbally indicated by the person handing the bags out).

Figure 19: Studies of relevance to behaviour change dependence on perception of potentially littered item

Author	Peer Review	Study method	For Hypo-thesis	Against Hypo-thesis	Notes
Loughborough University *report for Defra* (2010)	Yes	Interview of retailers and other stakeholders regarding whether customers had feedback regarding littering of degradable plastics	None	None	Stakeholders registered concern that PAC plastic promoted littering but no evidence provided for or against
Keep Scotland Beautiful (2007) cited in Brook Lyndhurst (2013)	No	Focus group and survey on litter	None	Yes	19% felt it was understandable to litter if the item is biodegradable or can rot away. No observation of actual behaviour. Perhaps had food items in mind.
S. Groner Associates *report for Keep Los Angeles Beautiful* (2009)	No	Focus groups and surveys of young people on litter	None	Yes	Respondents/participants reported more likely to litter if item biodegradable; cigarette butts thought of as biodegradable and hence acceptable to litter. No observation of actual behaviour
ENCAMS (2008)	No	Focus groups and survey – Smoking litter	None	Yes	Respondents excused littering of cigarette butts for reasons including that it was believed that cigarette butts are biodegradable. No observations of behaviour
Brook Lyndhurst (2015)	No	Focus groups and survey on litter	None	Yes	Biodegradability makes litter less unacceptable and lower priority for clean-up; occasionally plastic bags or paper items specifically referenced in relation to this characteristic. No observations of behaviour.
Keep America Beautiful (2009)	No	Survey on litter	None	Yes	22.6% said more likely to litter if item is biodegradable. This segment of respondents reported that they were more likely to litter than average. No behaviour observations.
Smith and Novotny (2011)	Yes	Review of tobacco industry focus group reports	Maybe	Yes/ Maybe	One focus group concluded smokers' 'perceived benefit of a biodegradable filter was 'the ability to litter without guilt'. Industry believed littering would increase or at least appear no better if biodegradable cigarette butts were introduced and this would harm, or at least not improve, their economic prospects through worsening or maintaining the status quo regarding their reputation and/or the imposition of regulation, with the corresponding influence on sales.

4.2.3 Hypothesis 8: PAC plastic is a possible solution to reduce the problems of plastic marine litter compared with conventional plastic.

The following section looks at the evidence base in respect of the effects of plastic in the marine environment on the aquatic ecosystem, as well as whether there is evidence that this leads to human health issues. Subsequent to this, we assess to the extent to which PAC plastic is expected to behave similarly, or differently, to conventional plastic with respect to these kinds of impacts.

4.2.3.1 Interactions of Plastics with Marine Organisms

The effects of anthropogenic debris in the marine environment on marine organisms have been documented for several decades. Plastic litter in the ocean can cause significant harm to marine organisms.

Entanglement of marine life occurs all over the world. A recent study reports that a high percentage of bird, turtle and mammal species have been recorded as entangled, including 100 % of marine turtles (7 of 7 species), 67 % of seals (22 of 33 species), 31 % of whales (25 of 80 species) and 25 % of seabirds (103 of 406).[134] Incidence appears to be increasing; taking the figures for birds, mammals and turtles, the number of species known to have been affected by entanglement has gone from 17% to 31% between similar literature reviews conducted in 1997 and 2014. Studies on the ingestion of plastic by fish and invertebrates are largely a recent development and hence the proportion of species known to be affected, calculated by assessing the literature, is not comparable over time. In total, entanglement has been observed in 344 species, as of 2014. Entanglement causes serious harm to marine life. Entangled organisms may no longer be able to acquire food and avoid predators, or become so exhausted that they starve or drown. Moreover, even if the organism does not die directly, wounds, restricted movements and reduced foraging ability will seriously affect the entangled animal.

In terms of ingestion, 331 species were documented to have been affected as of 2014. The extent of ingestion in marine organisms is increasing. The cited study found records of ingestion of plastic in 233 (44%) of bird, turtle and mammal species, while a similar study conducted in 1997 found evidence of ingestion in only 143 (27%) of bird, turtle and mammal species. Plastic ingestion can cause mortality directly or can affect animals by slower sub-lethal physical and chemical effects.[135]

Ingestion of plastic can lead to rapid death in marine animals when the gastrointestinal tract becomes completely blocked or severely damaged. This can occur even with small pieces of plastic if they are orientated in a particular direction inside the gastrointestinal tract. However, it is suggested that direct mortality from ingestion is probably a fairly infrequent phenomenon, and that indirect, sub-lethal effects from plastic ingestion are probably more

[134] Kühn, S., Rebolledo, E.L.B., and Van Franeker, J.A. (2015) Deleterious Effects of Litter on Marine Life, in Melanie Bergmann, Lars Gutow, and Michael Klages, (eds.), *Marine Anthropogenic Litter* (2015) Springer International Publishing

[135] Ibid.

widespread, with many individuals affected within populations. In the North Sea, 93% of fulmars were found to have ingested plastic.[136] The sub-lethal physical impacts of plastic ingestion may have various consequences, including but not limited to: [137]

- Stomach volume occupied by debris may limit optional food intake;
- Partial blockage of food passing through the digestive tract may cause gradual deterioration in body condition;
- The efficiency of digestive processes may be reduced; and
- The presence of plastic in the stomach may signal satiety to the brain, reducing the feeling of hunger, which may reduce the drive to search for food.

There are two further ways that plastics impact marine organisms and the marine ecosystem: by providing additional substrate for the proliferation and transport of marine life; and by smothering or abrading sea floor habitats.

By colonising floating plastic and 'rafting' to travel longer distances than otherwise possible, the extension of the range of certain species or the introduction of new ones can occur. Additionally, by providing more hard substrate for colonisation or reproductive activities, population numbers of certain species might increase.[138] This may cause very significant changes in population structure. One study predicted that global marine species diversity might decrease by as much as 58% if worldwide biotic mixing occurs.[139] As of 2012, 270 species had been reported rafting and 85 different species had been found using marine debris as a habitat (considered an underestimate by the authors of the review). [140]

Debris can smother benthic habitats. It has been suggested that the accumulation of debris on the sea floor might inhibit gas exchange between water within the sediment and the overlying water, resulting in decreased oxygen in the benthos that could alter the composition of life on the sea floor.[141] An Indonesian study showed that there were fewer diatoms in the sediments underneath marine debris but more small invertebrates.[142] In another example, the level of marine debris cover and coral cover was found to be

[136] van Franeker, J.A., Blaize, C., Danielsen, J., et al. (2011) Monitoring plastic ingestion by the northern fulmar Fulmarus glacialis in the North Sea, *Environmental Pollution (Barking, Essex: 1987)*, Vol.159, No.10, pp.2609–2615

[137] Kühn, S., Rebolledo, E.L.B., and Van Franeker, J.A. (2015) Deleterious Effects of Litter on Marine Life, in Melanie Bergmann, in Melanie Bergmann, Lars Gutow, and Michael Klages, (eds.), *Marine Anthropogenic Litter* (2015) Springer International Publishing

[138] Goldstein, M.C., Rosenberg, M., and Cheng, L. (2012) Increased oceanic microplastic debris enhances oviposition in an endemic pelagic insect, *Biology Letters*, p.rsbl20120298

[139] Mckinney, M.L. (1998) On predicting biotic homogenization: species-area patterns in marine biota, *Global Ecology & Biogeography Letters*, Vol.7, No.3, pp.297–301

[140] STAP/GEF (2012) *Impacts of marine debris on biodiversity: Current status and potential solutions*, Report for CBD, 2012

[141] Goldberg, E.D. (1997) Plasticizing the Seafloor: An Overview, *Environmental Technology*, Vol.18, No.2, pp.195–201

[142] Uneputty, P., and Evans, S.M. (1997) The impact of plastic debris on the biota of tidal flats in Ambon Bay (eastern Indonesia), *Marine Environmental Research*, Vol.44, No.3, pp.233–242

negatively correlated, with debris abundance associated with decreasing species diversity, in the South Pacific.[143]

4.2.3.2 Impacts of Microplastics on the Marine Environment

The small size of microplastics (smaller than 5mm) enables them to interact with a particularly wide range of marine organisms. Microplastics, i.e. those with a diameter of less than 5mm, can affect the very base of the marine food chain via ingestion or adsorption. Marine algae which adsorb microplastics onto their surface demonstrated inhibited photosynthesis and oxidative stress in a laboratory setting. Laboratory studies have also shown that lugworms, amphipods, blue mussels and sea cucumbers ingest microplastics. Zooplankton, seabirds and fish are all known to ingest microplastics in their natural environment. Direct microplastic ingestion by marine mammals has so far only been observed in seals. Further work is required to assess if microplastics significantly affect marine mammals. Secondary ingestion is one such route by which this may occur. [144]

4.2.3.3 Impacts of Toxic Substances Associated with Plastic Debris on Marine Organisms

Plastics contain a variety of potentially toxic chemicals incorporated during manufacture, which could be released to the environment.[145] Research has identified that many of these chemicals can have toxicological effects on fish, mammals and molluscs, hence a hazard could exist if plastic fragments containing these chemical are ingested by marine organisms.[146] Furthermore, plastic debris can adsorb persistent organic pollutants (POPs) that are present in the oceans from other sources. Within a short timeframe these substances can become orders of magnitude more concentrated on the surface of the plastic debris than in the surrounding water column, presenting a second mechanism by which toxic chemicals in plastics could be transferred to marine organisms upon ingestion.[147] The potential impacts of these chemicals on marine organisms are further outlined in this section.

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[143] Richards, Z.T., and Beger, M. (2011) A quantification of the standing stock of macro-debris in Majuro lagoon and its effect on hard coral communities, *Marine Pollution Bulletin*, Vol.62, No.8, pp.1693–1701

[144] Kühn, S., Rebolledo, E.L.B., and Van Franeker, J.A. (2015) Deleterious Effects of Litter on Marine Life, in Melanie Bergmann, in Melanie Bergmann, Lars Gutow, and Michael Klages, (eds.), *Marine Anthropogenic Litter* (2015) Springer International Publishing

[145] Lithner, D., Larsson, Å., and Dave, G. (2011) Environmental and health hazard ranking and assessment of plastic polymers based on chemical composition, *Science of The Total Environment*, Vol.409, No.18, pp.3309–3324

[146] Oehlmann, J., Schulte-Oehlmann, U., Kloas, W., et al. (2009) A critical analysis of the biological impacts of plasticizers on wildlife, *Philosophical Transactions of the Royal Society B: Biological Sciences*, Vol.364, No.1526, pp.2047–2062

[147] Teuten, E.L., Saquing, J.M., Knappe, D.R.U., et al. (2009) Transport and release of chemicals from plastics to the environment and to wildlife, *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, Vol.364, No.1526, pp.2027–2045

Hazards Associated with Plastic Ingredients

Additive ingredients such as plasticisers and flame retardants are not usually bound to the polymer matrix, and can leach from plastics.[148] These chemicals may therefore become bioavailable to marine life after ingestion. Experimental studies have shown that phthalates (a kind of plasticiser) affect reproduction in all study species, impairing development in crustaceans and amphibians, and generally inducing genetic aberrations.[149] Adverse effects related to brominated flame-retardants in man and wildlife include neurobehavioural development disorders, thyroid hormone alterations, and reduction in reproduction.[150] While for some substances, toxicity occurs at greater levels than found in the environment, for several, adverse effects have been documented at environmentally relevant concentrations.[151]

For some plastics, the monomer that makes up the polymer itself is classified as hazardous. For example, polyurethane foam, PVC, polycarbonate (e.g. bisphenol A) and high-impact polystyrene are all composed of monomers that can be considered carcinogenic, mutagenic or toxic for reproduction.[152]

Hazards Associated with Sorbed Pollutants

When plastic becomes marine debris, it can accumulate several other pollutants from the surrounding seawater, including several POPs and metals. Research has shown that many of these pollutants can disrupt the key physiological processes of marine organisms, causing disease and reducing the ability to escape predators and reproduce.[153] A number of observational studies have provided further evidence that the complex mixture of plastic and sorbed pollutants can have a harmful impact on marine organisms. For example, after a two-month dietary exposure to plastic with a mixture of POPs and metals, in one study, fish suffered from liver toxicity and showed signs of endocrine disruption.[154]

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[148] Lithner, D., Nordensvan, I., and Dave, G. (2012) Comparative acute toxicity of leachates from plastic products made of polypropylene, polyethylene, PVC, acrylonitrile–butadiene–styrene, and epoxy to Daphnia magna, *Environmental Science and Pollution Research*, Vol.19, No.5, pp.1763–1772

[149] Oehlmann, J., Schulte-Oehlmann, U., Kloas, W., et al. (2009) A critical analysis of the biological impacts of plasticizers on wildlife, *Philosophical Transactions of the Royal Society B: Biological Sciences*, Vol.364, No.1526, pp.2047–2062

[150] Darnerud, P.O. (2003) Toxic effects of brominated flame retardants in man and in wildlife, *The State-of-Science and Trends of BFRs in the Environment*, Vol.29, No.6, pp.841–853

[151] Oehlmann, J., Schulte-Oehlmann, U., Kloas, W., et al. (2009) A critical analysis of the biological impacts of plasticizers on wildlife, *Philosophical Transactions of the Royal Society B: Biological Sciences*, Vol.364, No.1526, pp.2047–2062

[152] Lithner, D., Larsson, Å., and Dave, G. (2011) Environmental and health hazard ranking and assessment of plastic polymers based on chemical composition, *Science of The Total Environment*, Vol.409, No.18, pp.3309–3324

[153] Vasseur, P., and Cossu-Leguille, C. (2006) Linking molecular interactions to consequent effects of persistent organic pollutants (POPs) upon populations, *Chemosphere*, Vol.62, No.7, pp.1033–1042

[154] Rochman, C.M., Hoh, E., Kurobe, T., and Teh, S.J. (2013) Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress, *Scientific Reports*, Vol.3

4.2.3.4 Food Web Transport

There are several lines of evidence to suggest that chemical contaminants can transfer from plastic debris to marine animals. For example, evidence from both field and laboratory studies demonstrate a positive correlation between concentrations of PCBs (synthetic organic chemical compounds which are toxic to animals and humans), and also trace metals, in sea birds and the amount of plastic ingested.[155] Studies of plastic-derived chemicals in seabirds collected from the North Pacific and fish collected from the South Atlantic found similar types of polybrominated diphenyl ethers (PBDEs) (a type of brominated flame retardant commonly used in plastics) in both the animal's tissues and the ingested plastic found in their gut content.[156] Similar results have been achieved in controlled laboratory studies. Two such studies, of fish and lugworms respectively, also demonstrated that, as well as 'primary' plastic chemicals, POPs which have accumulated in the ocean and become sorbed to plastics are also transferred into animal tissues upon ingestion.[157] [158]

Specific evidence of marine litter in food targeted for human consumption is beginning to emerge. A study of microplastics in two species of bivalves commercially grown in Belgium, the blue mussel and the oyster, found microplastics in both species.[159] In 2015, *Rochman et al.* analysed fish and shellfish from markets in Indonesia and California.[160] They found anthropogenic debris in 25%-28% of individual fish and in 33% of individual shellfish sampled.

Potential Health Risks

If microplastics previously ingested by marine organisms were consumed by humans, the health risks from these plastic particles would depend on the degree to which chemicals derived from these plastics, as well as the actual plastic particles, can be transferred to human body tissues. These interactions have been studied in a different context, that is, the use of microplastics as a potential pharmaceutical drug delivery system. The studies

[155] Teuten, E.L., Saquing, J.M., Knappe, D.R.U., et al. (2009) Transport and release of chemicals from plastics to the environment and to wildlife, *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, Vol.364, No.1526, pp.2027–2045

[156] Tanaka, K., Takada, H., Yamashita, R., Mizukawa, K., Fukuwaka, M., and Watanuki, Y. (2013) Accumulation of plastic-derived chemicals in tissues of seabirds ingesting marine plastics, *Marine Pollution Bulletin*, Vol.69, Nos.1–2, pp.219–222

[157] Browne, M.A., Niven, S.J., Galloway, T.S., Rowland, S.J., and Thompson, R.C. (2013) Microplastic Moves Pollutants and Additives to Worms, Reducing Functions Linked to Health and Biodiversity, *Current Biology*, Vol.23, No.23, pp.2388–2392

[158] Rochman, C.M., Lewison, R.L., Eriksen, M., Allen, H., Cook, A.-M., and Teh, S.J. (2014) Polybrominated diphenyl ethers (PBDEs) in fish tissue may be an indicator of plastic contamination in marine habitats, *Science of The Total Environment*, Vol.476–477, pp.622–633

[159] Van Cauwenberghe, L., and Janssen, C.R. (2014) Microplastics in bivalves cultured for human consumption, *Environmental Pollution*, Vol.193, pp.65–70

[160] Rochman, C.M., Tahir, A., Williams, S.L., et al. (2015) Anthropogenic debris in seafood: Plastic debris and fibers from textiles in fish and bivalves sold for human consumption, *Scientific Reports*, Vol.5, p.14340

conducted to date suggest that there is ample opportunity, following ingestion, for microplastics in food to enter, circulate and bioaccumulate within the body.[161]

The studies reviewed in the section suggest that plastic-associated chemicals from plastic can transfer to wildlife tissues upon ingestion. However, they do not provide an indication of whether the transfer of chemicals from plastic to marine organisms is widespread, or whether interaction with plastic pollution is a significant deliverer of chemical contamination into the foodweb compared with other pathways, i.e. by chemically contaminated food ingestion or uptake of chemicals from ambient water. In other words, these studies do not indicate if microplastic-mediated chemical transfer poses additional risk to wildlife, or indeed humans.

4.2.3.5 Impacts of PAC Plastics versus Conventional Plastics

In the previous sections, the different impacts of plastics in the marine environment have been reviewed. For many of the impacts, the effects at population level have not been established, although the basal evidence for the mechanisms by which population level impacts could be occurring is becoming more robust over time. However, it is important to note that it is not the purpose of this section to make definitive conclusions regarding what the marine impacts of plastics are in general, but only to assess whether using PAC plastics is likely to reduce, or increase, these impacts.

The key differentials between conventional and PAC plastics are:

- The timeframe over which degradation into smaller pieces and compounds of increasingly lower molecular weight occurs; and
- The location that this occurs in, and the implications for how likely it is for the plastic to find its way into the marine environment.

It can be reasoned that:

- On land and on the sea surface, PAC plastics degrade into smaller pieces quicker than conventional plastics as a consequence of exposure to UV light and physical abrasion owing to wind, water and waves.
- Unfragmented, it can be expected that PAC plastic is equally as likely to end up in the marine environment as conventional plastic. Fragmented plastic, on the other hand, can be expected to be less likely to get snagged on plant material or filtered out by drains, and subsequently recovered via litter picking / litter removal processes. Fragmented plastic will also require less force from wind and water to move it, and is therefore likely to have a greater propensity to travel to the marine environment.
- On the other hand, some fragmented PAC plastic may also undergo complete biodegradation on land without being mobilised, and as such would not move to the marine environment. Whether more or less plastic will reach the marine environment, and in what form it arrives, can be expected to relate to a balance of

[161] Garrett, N.L., Lalatsa, A., Uchegbu, I., Schätzlein, A., and Moger, J. (2012) Exploring uptake mechanisms of oral nanomedicines using multimodal nonlinear optical microscopy, *Journal of Biophotonics*, Vol.5, Nos.5–6, pp.458–468

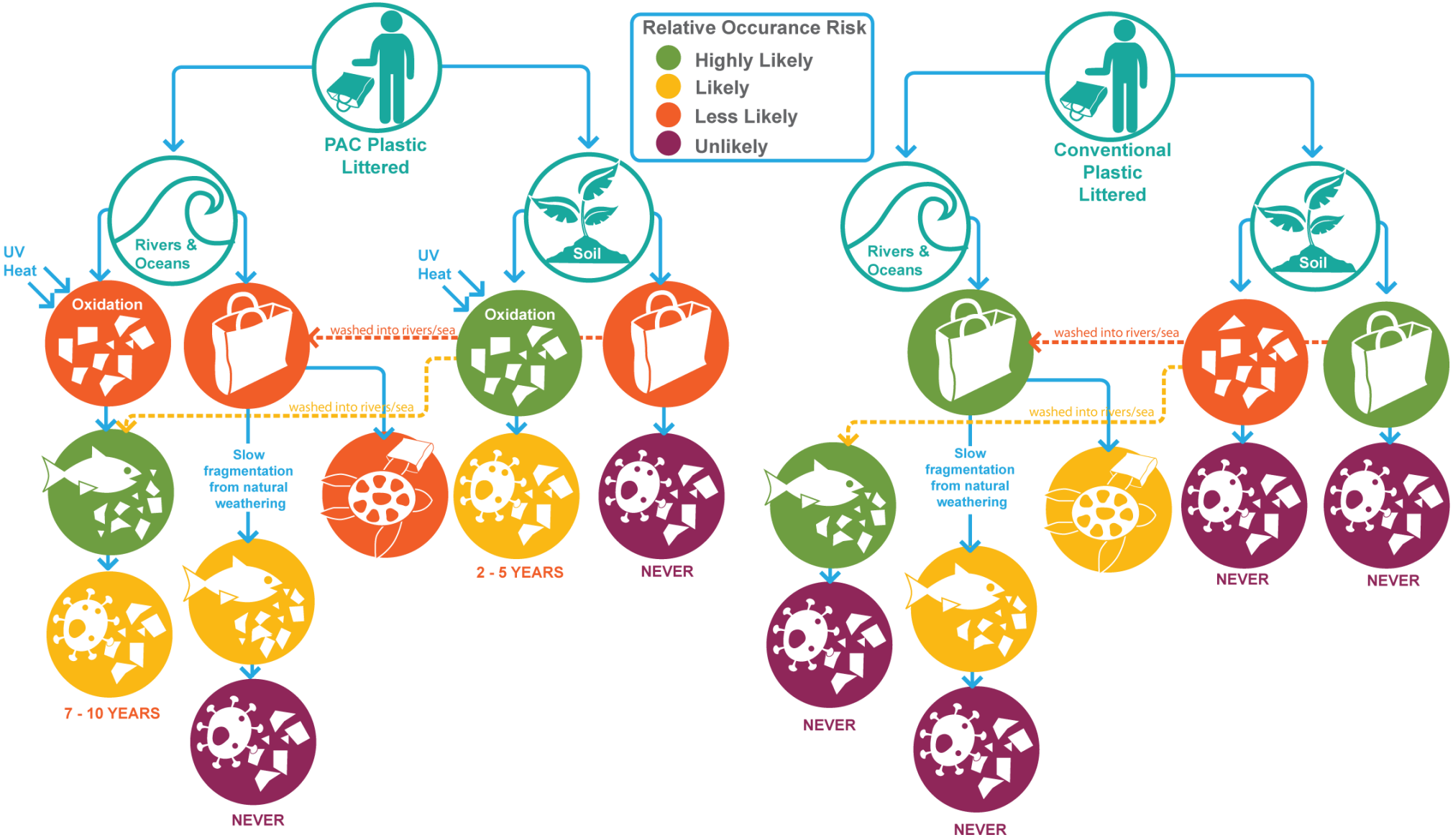
probabilities between fragments fully biodegrading in situ and those which are mobilised by wind and/or water before complete biodegradation occurs. It is not possible to conclude either way on this issue. The reduced opportunity for litter picking and greater propensity for fragmented plastic to be mobilised might increase the flow of plastic to marine environments; alternatively, the flow may be decreased as a result of PAC plastic biodegrading in a shorter timescale. Nonetheless, it would be reasonable to assume that, of the plastic which arrives in the marine environment, PAC plastic can be expected to be more fragmented, as well as having a greater tendency for further fragmentation.

- Reflecting the discussions under hypothesis 5 in Section 4.1.5, a very slow rate of degradation is expected in the water column and on the sea bed. Over time, the plastic may then fragment into smaller particles that still preserve the chemical properties of plastic before any biodegradation can take place.

Based on the above assumptions Figure 20 conceptualises the relative flows of littered plastic bags into soil and marine environments. The likelihood of each step occurring is colour coded to show which pathways are considered to have the greatest risks (relatively speaking). For example, PAC plastic that is littered into soil is more likely to fragment than conventional plastic. If this occurs, fragmented plastic may be washed into the seas/rivers where it is highly likely they will contribute to microplastics. Finally, compared to conventional plastics, fragmented PAC plastic has a higher likelihood of biodegradation in a marine environment within the indicative 7—10 year timeframe (based on the best case evidence provided in Section 4.1.5). The likelihood of the littering of each material taking place is not accounted for, as there is insufficient evidence to suggest whether the magnitude is sufficiently different between the two to make a significant impact.

The timeframes over which marine impacts may be expected to occur (i.e. the 'impact profile' over time) for conventional and PAC plastics are considered further in the following subsections.

Figure 20: Conceptualised Littering Pathways for PAC relative to Conventional Plastic



Entanglement, Smothering and Abrasion

The propensity of an item of debris to cause entanglement depends on its physical shape. Elongated (cord-like) items, items with any kind of loops or openings, including nets, bags and containers, all pose an entanglement risk as long as these features are not broken.

PAC plastics entering the marine environment whole will initially have the same impact as conventional plastics of the same shape. This will continue for as long as the hazardous physical features remain intact. Differentiation in impact will start to occur if breakdown of the features occurs sooner in PAC plastic, which is likely to be the case. PAC plastics entering the marine environment as fragments are also less likely to cause entanglement impacts, and they are more likely to enter as fragments than conventional plastics.

We also postulate that smothering and abrasion impacts are likely to be worse for larger objects, with a larger surface area, compared to many smaller items of the same overall area, because distributed damage is less disruptive to a habit than contiguous areas.

PAC plastics entering the marine environment whole will have the same impact in terms of smothering/abrasion as conventional plastics until they start to break down. If PAC plastics are more likely to enter the marine environment fragmented as compared to conventional plastics as we have assumed, the smothering/abrasion effects may be diminished. At an undefined lower size limit, plastics cease to have an impact through smothering or abrasion. This lower size limit can be expected to be reached earlier for PAC plastic than for conventional plastics. Therefore in terms of lifetime impact, PAC plastics will have reduced impact, though it is not possible to quantify this. The size threshold at which impacts are reduced is likely to be much larger than for ingestion or rafting impacts. Importantly, PAC plastics should not be expected to eliminate smothering/abrasion impacts.

When considering entanglement impacts over time, although PAC plastics may be less harmful than conventional plastics, we do not have the evidence needed to estimate how much less. Also, the impacts are not eliminated. This is summarised in Table 8.

Table 8: Likelihood of Entanglement, Smothering and Abrasion

Material	Likelihood of Entanglement, Smothering and Abrasion	Symbol
Conventional Plastic Bag	Conventional plastic bags are ***likely*** to become a risk if they enter the ocean whole. It is ***highly likely*** that they will be whole if they enter the ocean.	
PAC Plastic Bag	PAC plastic bags are ***less likely*** to become a risk if they enter the oceans whole. It is ***less likely*** that they will be whole when they enter the ocean.	

Ingestion

The propensity of an item to be ingested depends upon its size as well as the species concerned. For example, whales have been known to ingest large items, with a recent example being the discovery of a 70 cm piece of plastic from a car in the stomach of a beached sperm whale.[162] At the other end of the scale, plastics found to have been ingested by zooplankton in nature were in in the 0.5-1mm range, and–in the lab–much smaller particles of plastic 1.7-30.6µm were consumed.[163, 164] Additionally, the number of items in the environment is likely to be correlated with ingestion rates.[165] Buoyancy, or propensity to circulate, will also influence the availability of the item for ingestion—this also depends on the potential 'ingester' and where it is located.

Therefore, ingestion is a hazard over a wide range of sizes. As an item fragments, the following consequences follow:

- There are more items, presenting more opportunities for ingestion; and
- The number of species and individuals that can ingest the item increases (generally speaking, population size is larger the smaller is the species' body size).[166]

It follows that PAC plastics entering the marine environment whole initially have the same propensity to be ingested as conventional plastics. In comparison, plastics entering as fragments have a greater propensity to be ingested: it can be reasoned that PAC plastic is more likely to enter as fragments than conventional plastics, which is an important determinant of impact. Although no known study to date has explored the issue, an acceleration of the time before fragmentation may decrease the opportunity for litter clearance (or the possibility of natural burial in soil etc.) and increase the propensity of the items to be carried to the sea by wind and water. Therefore in the short- to medium-term, PAC plastics may have a greater impact in terms of ingestion than conventional plastics. PAC plastic could have the effect of bringing forward in time the ingestion impacts compared to conventional plastics, along with the potential for increased impacts should the likelihood of PAC plastics entering the marine environment be increased.

There is no established lower size threshold at which plastics no longer present ingestion hazards to any species. However, it is reasonable to assume that there is one – a point at which the plastic ceases to cause direct physical damage to the digestive system or indirect effects on the digestive process or satiety. This is likely to be larger for larger animals and

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[162] Ministerium für Energiewende, Landwirtschaft, Umwelt und ländliche Räume, Schleswig-Holstein, Press release, 23/03/2016 http://www.schleswig-holstein.de/DE/Landesregierung/V/Presse/PI/2016/0316/MELUR_160323_Untersuchungsergebnisse_Pottwale.html

[163] Desforges, J.-P.W., Galbraith, M., and Ross, P.S. (2015) Ingestion of Microplastics by Zooplankton in the Northeast Pacific Ocean, *Archives of Environmental Contamination and Toxicology*, pp.1–11

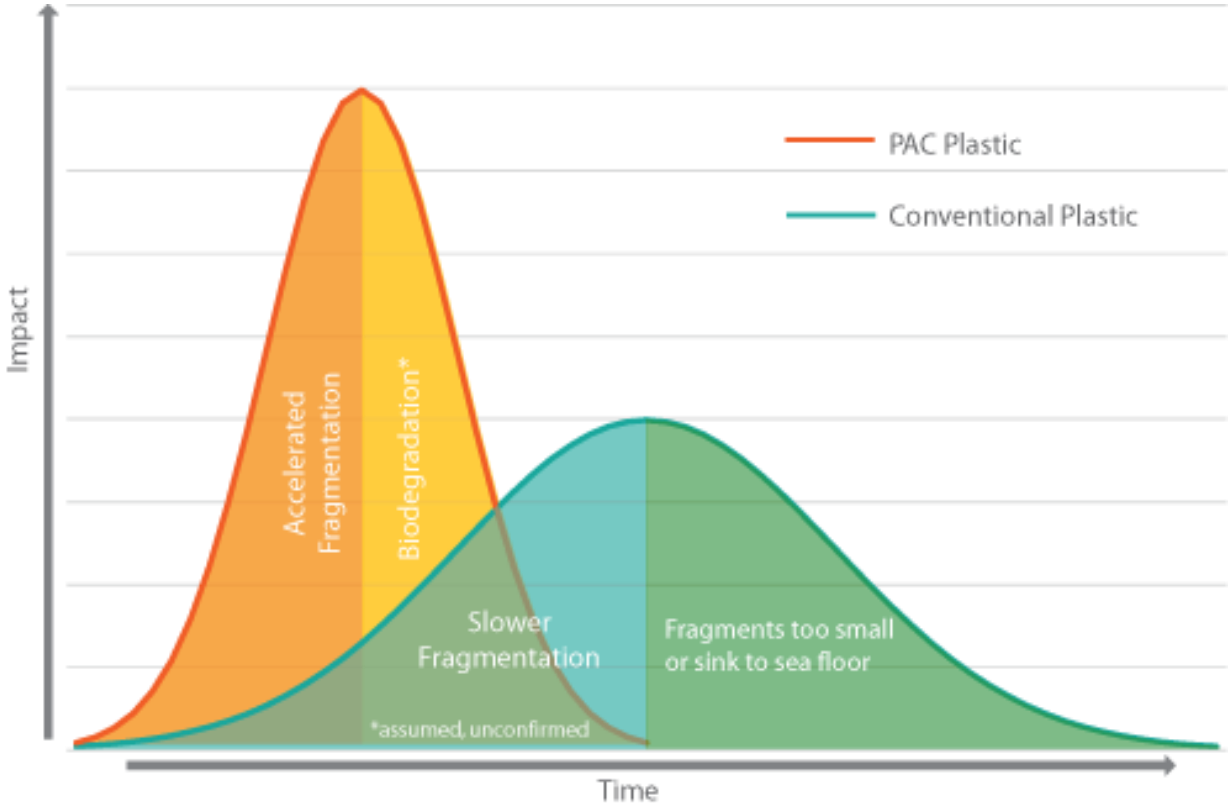
[164] Cole, M., Lindeque, P., Fileman, E., Halsband, C., Goodhead, R., Moger, J., and Galloway, T.S. (2013) Microplastic Ingestion by Zooplankton, *Environmental Science & Technology*, p.130606145528005

[165] van Franeker, J.A., Heubeck, M., Fairclough, K., et al. (2005) *'Save the North Sea' Fulmar Study 2002–2004: A Regional Pilot Project for the Fulmar-Litter-EcoQO in the OSPAR Area*, 2005, http://www.vliz.be/imisdocs/publications/72498.pdf

[166] Cotgreave, P. (1993) The Relationship Between Body Size and Population Abundance in Animals, *Trends in Ecology & Evolution*, Vol.8, No.7, pp.244–248

smaller for smaller organisms. PAC plastics will reach this point sooner than conventional plastic. Because of this, the ingestion impacts of PAC plastics over their marine lifetime may be lower than conventional plastic assuming that the propensity to be ingested is reduced in time by plastic reaching the lower size thresholds more quickly. Quantifying the extent to which this is true is not currently possible given the present state of knowledge about the lifecycle of plastics in the marine environment. However, any reduction in the propensity for plastic fragments to be ingested may be counterbalanced by a higher peak in frequency distribution for PAC plastics over a shorter time period. For example, impacts will be felt by a greater proportion of individuals within a population and proportion of species, which may challenge the capacity of an ecosystem to absorb those impacts over the shorter time period. Higher ingestion concentrations at one time point are likely to be more detrimental to any given individual. This hypothesis is described graphically in Figure 21. The area under both lines is roughly equal—indicating a similar overall impact—but the impacts of PAC plastic are greater for a shorter period, whereas conventional plastic's impacts are smaller for a greater period of time. At this moment it is not possible to quantify either of the two axis in terms of the relative impacts or timescale involved.

Figure 21: Conceptual PAC/Conventional Microplastic Impact Comparison



Additionally, borrowing a widely applicable principle from economics, benefits or dis-benefits in the future are smaller in present day values – they are "discounted" – compared to benefits or dis-benefits experienced in the present. Nonetheless, it may also be reasoned that even if accelerated fragmentation were to reduce the propensity in time to be ingested, the same property may also mobilise greater amounts of plastic to enter marine environments and reduce possibility for litter removal, constituting another factor that may outweigh any improvement.

It remains true that ingestion impacts are not eliminated for PAC plastics.

The comparative likelihood of ingestion is shown in Table 9. This shows that the risk is assumed to be similar although the risk may be slightly higher for PAC plastic if we assume that the microplastic fragments are more likely to be mobilised towards rivers and oceans.

The relative *impacts* of ingestion are summarised in Table 10. This takes into account the timescales where a short term 'spike' (as demonstrated in Figure 21) may be more impactful than spreading the propagation of microplastics over the longer term.

Table 9: Likelihood of Ingestion Risk (Microplastic Formation)

Material	Likelihood of Ingestion Risk (Microplastic Formation)	Symbol
Conventional Plastic Bag	Conventional plastic bags are ***highly likely*** to become a risk if they enter the ocean as a microplastic. It is ***less likely*** that they will enter the ocean as a microplastic but it is ***highly likely*** that they will become a microplastic (albeit in a longer timeframe than for PAC plastic).	
PAC Plastic Bag	PAC plastic bags are ***highly likely*** to become a risk if they enter the ocean as a microplastic. It is ***more likely*** that they will enter the ocean as a microplastic than for conventional bags. It is also likely that they will fragment to microplastics in a reduced time period, effectively increasing instantaneous microplastic concentrations.	

Accumulation and Transport of Toxic Substances

Regarding the accumulation and transport of toxic substances, it is important to understand how quickly plastic reaches maximal absorption of these hydrophobic organic compounds (so-called 'equilibrium'), and what influences this and to what extent.

For example, if it took a sizeable and greater proportion of the lifespan of PAC plastics at sea for these compounds to accumulate to the same level as in conventional plastics, we might start to judge that the potential impacts of this accumulation would be lessened for PAC plastics.

However the evidence tells us that maximal absorption is reached in relatively short timescales – days for very small microplastics (smaller than a millimetre) and months for microplastics of the size of pre-production pellets (a few mm across) (see Table A - 3 in Appendix A.2.0). A general trend is that polypropylene takes less time than polyethylene (carrier bags are usually made from polyethylene); one study showed that LDPE takes less time to reach maximal sorption than HDPE (carrier bags can be made of either). Another trend is that weathered plastic may have a higher capacity to absorb pollutants and that this

takes longer per unit of pollutant than virgin plastic; however, the time to maximal absorption is still in the order of months.[167]

Regardless of the factors causing variation in the time taken to maximal sorption, it seems likely that this occurs well before PAC plastics will complete their lifecycle and hence behave similarly to conventional plastics. The impact profile over time is expected therefore to follow that for ingestion, but specifically for microplastic ingestion, as the increased surface area to volume ratio means that sorption and desorption can happen more quickly, speeding the transfer of toxic substances. The fact that weathering may increase the capacity of plastics to absorb pollutants will further potentiate the impact of PAC plastics, if they attain the characteristics of weathering sooner than conventional plastics.

As per the discussion above, the time point at which PAC plastics produce a maximal quantity of microplastics will be significantly sooner than conventional plastics, along with the impacts of plastic-associated chemicals. The lower size threshold at which these impacts stop occurring is not known; however, this will also occur sooner in PAC plastics than conventional plastics.

Summary

Table 10 summaries the interval after which plastic enters the marine environment that it is expected to have the listed impact and the point at which the impact is expected to cease or diminish. The implications for PAC plastics are considered and ranked according to how similar their impacts relative to conventional plastics (1=impact is reduced, 3 =impact is increased).

The table demonstrates that the impacts are potentially lessened for entanglement and smothering due to the lower likelihood of the plastic entering the marine environment whole. The impacts, both physical and toxicological of the ingestion of microplastics are considered to increase due to the relative increase in the number of microplastics—due to greater mobilisation—and the higher concentration of these impacts—due to the propensity to fragment quicker—over a shorter space of time.

[167] Karapanagioti, H.K., and Klontza, I. (2008) Testing phenanthrene distribution properties of virgin plastic pellets and plastic eroded pellets found on Lesvos island beaches (Greece), *Marine Environmental Research*, Vol.65, No.4, pp.283–290

Table 10 Impact of Plastic on the Marine Environment over Time and Implication for Impact of PAC Plastic, Ranked by Similarity to Lifetime Impacts of Conventional Plastic. (1=impact is reduced, 3 =impact is increased)

Impact	Characteristic of plastic	Start of impact	Development	End of impact	Implication for PAC plastic	Relative Impact
Entanglement	Intact shapes: Cord-like nature, looped features, openings	Immediate	Impact remains as long as hazardous shape remains intact	Impact ended if degradation leads to disintegration of shape.	If PAC plastic is more likely to enter the marine environment fragmented (microplastics), or if hazardous feature broken down earlier, impact reduced.	**1**
Smothering and Abrasion	Size, density i.e. sinking plastic.	Immediate	Impact decreases over time as item fragments.	Lower dimension threshold uncertain. Intermediate entanglement and ingestion impacts.	If PAC plastic is more likely to enter the marine environment fragmented (microplastics), or if hazardous feature broken down earlier, impact reduced.	**1**
Ingestion (physical consequences)	Size; also the related feature, frequency.	Immediate	Impact increases as item fragments – more species can ingest and more pieces to ingest	At some undefined point for each species lower size threshold for impact reached. Likely to be small.	• More microplastics due to increased fragmentation • Impacts brought forward in time. • Lifetime impacts may be reduced to some extent if accelerated degradation avoids ingestion. • Marine impacts may also be increased because of higher proportion of individuals/species impacted at one time and higher concentrations within individuals. • Accelerated degradation might also increase absolute quantities of plastic entering the marine environment.	**3**
Accumulation and transport of toxic substances	Time taken for maximal sorption to be reached	Days or months depending on size. Larger= longer	Impacts increase over time as fragmentation continues, items become smaller, reach maximal sorption faster and are greater in number	Unknown lower size threshold at which impacts end.	• PAC plastics expected to have impacts sooner, though end earlier, hence lifetime impacts may be reduced to some extent. • Marine impacts may also be increased because of higher proportion of individuals/species impacted at one time and higher concentrations within individuals. • Accelerated degradation might also increase absolute quantities of plastic entering the marine environment. Impacts not eliminated.	**3**

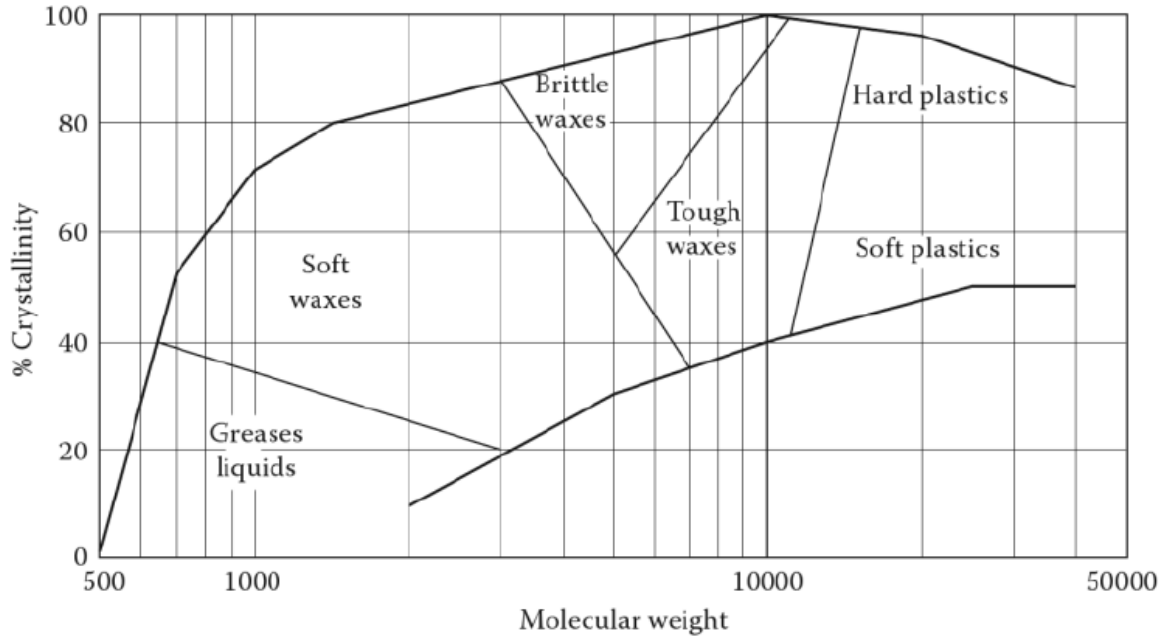
4.2.3.6 Issues Related to Molecular Weight

Alongside the issues of the potential impacts that PAC plastic can have in the marine environment, it is also important to address issues surrounding whether low molecular weight plastic can still be considered a plastic. The PAC plastics industry argue that below 5,000 Dalton, PAC plastic is no longer plastic and will not behave in the same way as conventional plastic.

This issue has already been highlighted in a report[168] for the European Commission investigating plastic 'microbeads' that appear in some cosmetics. It was also speculated that other lower molecular weight 'waxes' could also be an environmental issue.

Figure 22 shows that polyethylene of a molecular weight of 5,000 could be considered in the realms of soft-brittle waxes.

Figure 22: Physical Properties of Polyethylene



Source: Engineering Design with Polymers and Composites[169]

In order to investigate this further it is useful to look at other low molecular weight polymers and whether they have been observed to biodegrade in the marine environment. Polyethylene glycol (PEG) is a commonly used polymer in cosmetics. A

[168] Eunomia Research & Consulting (2016) *Study to support the development of measures to combat a range of marine litter sources*, Report for European Commission DG Environment, 2016
[169] James C. Gerdeen(2005) *Engineering Design with Polymers and Composites*, CRC Press

recent study[170] looked into the degradability of PEG in waste water treatment (WWT), fresh water and sea water. Bacteria from each source were used to simulate the conditions for each environment. Complete biodegradation was observed for all grades of PEG up to a molecular weight of 57,800 in WWT sludge and fresh water. In sea water PEG over 7,400 was only partially degradable. It took around 100 days for PEG with a MW of 4,500 to biodegrade. PEG with a MW of 14,600 only biodegraded by 40% over 180 days—and degradation had levelled off from 50 days onwards.

This confirms that—certainly for PEG—that the lower MW polymers will biodegrade much more freely in sea water. It also appears that complete biodegradation may not occur over 5,000 Dalton.

In applying these findings to PAC plastic, it should also be recognised that the abiotic and biotic degradation processes will not take place entirely one after the other, but can happen concurrently. As areas of the PAC plastic reduce to a low molecular weight these areas may become bioavailable while the rest of the material continues to biotically degrade. By comparison, this action is not promoted in conventional plastics (or PEG). What these results indicate is that materials must be sufficiently reduced in MW to become bioavailable. If, for any reason, this process is not allowed to happen or is incomplete, then there is a significantly greater risk of the PAC plastic remaining in a polymer state. As it is difficult or even impossible to control exactly what happens to the PAC plastic once it is littered, it cannot be assumed that abiotic processes will take place sufficiently in all cases and situations.

[170] Bernhard, M., Eubeler, J.P., Zok, S., and Knepper, T.P. (2008) Aerobic biodegradation of polyethylene glycols of different molecular weights in wastewater and seawater, *Water Research*, Vol.42, No.19, pp.4791–4801

4.2.3.7 Conclusion

Hypothesis 8: PAC plastic is a possible solution to reduce the problems of plastic marine litter compared with conventional plastic.

Inconclusive. The evidence is insufficient to conclusively judge this hypothesis. Some marine litter impacts could be reduced by PAC plastic, but others could be exacerbated.

The physical and chemical characteristics of PAC versus conventional plastics are expected to be similar over extended phases of the lifecycle of PAC plastics, with sometimes reduced lifetime impacts, and sometimes accelerated lifetime impacts.

The accelerated degradation of PAC plastics can be expected, in some ways, to worsen the impacts of plastics on the marine environment. However the same characteristic can also alleviate other types of impact. Importantly, the overall impacts of plastics on the marine environment are ***not mitigated***.

The impacts can be related to the size range for marine plastics at which a certain impact occurs, and the frequency distribution of PAC plastics and conventional plastics over time. Uncertainties around the lower size thresholds at which different impacts stop occurring, as well as around the exact development of the frequency distribution of the compared types of plastic over time, mean that the reductions (or increases) cannot be easily quantified. We might, however, expect reductions in entanglement and smothering impacts for PAC plastic. Other impacts may, however, be expected to increase. With fragmented plastic concentrated into a shorter time period in the case of PAC plastic, this would be expected to increase the proportion of individuals, species and habitats affected, and the burden of impacts for an individual of a species. This poses a greater challenge for individuals and ecosystems to adapt and recover from impacts.

As species level effects of marine plastic have not been conclusively established for conventional plastic, it is similarly not possible to conclude on the effects of PAC plastic. The only method available is to assess the comparative impacts. By undertaking this exercise we find that—based on the current understanding of pathways and possible impacts—we can only say that PAC plastic is likely to increase impacts in some areas, and reduce them in others. Compared to smothering impacts, it could be considered that ingestion impacts and the transport of toxic substances are more of an issue for the food chain as a whole, with potential for subsequent negative human impacts. These links are still being established, but it should be expected that they pose a greater risk to species as a whole—depending on their propensity to ingest microplastics and accumulation issues—than accidental occurrences of entanglement. Therefore, although we are not able to come to any conclusive judgement on the hypothesis, on balance of the impacts between PAC and conventional plastic for the marine environment, concerns remain that PAC plastics do not eliminate impacts, and also that impacts may be increased in certain important impact categories.

4.3 Issues Relating to Recycling Processes

Where the intended effect is to encourage fracturing and rapid degradation of plastic bags, the presence of pro-oxidant additives in plastic polymers is desirable to fulfil this function. However, where degradation would impair long life requirements (for instance in all manner of solid plastic products), or where tensile and longevity properties are important (in products ranging from cling film to damp proof membranes and landfill liners), any pro-oxidant additives present in polymers due to PAC plastics in recycling streams incites quality concerns and even potential risks of environmental hazard.

To contextualise the issues, it is useful first to define how plastics recycling systems are currently organised for both rigid and flexible packaging. The implications for material supply chains once end of waste status is achieved are also of interest, so that the impacts of PAC plastic within the material streams can be diagnosed. The transformation of waste plastic into recyclates takes place in several stages, notably: collection, sorting, bailing, crushing, reprocessing, conversion and manufacture of new plastic products.

For rigid packaging plastics, recycling systems are well established. Recovered plastics are sorted either by hand or through mechanised processes often using near infra-red (NIR) technology and a series of conveyors and air knives to separate grades of plastic. To achieve closed loop recycling, single polymer grades are required. There is also a preference for material clarity, since dyed plastics tend to end up in a 'jazz' material stream for which recycling applications are more limited. Following the sorting processes that attempt to isolate colour and polymer types, the next stage is size reduction operations (to shreds, flakes or regrind), followed by cleaning, agglomeration and shaping into pellet or powder form. At this point end of waste criteria is achieved with the material becoming a product which can be marketed for manufacture of new products.

Evidence from a study into a number of facilities sorting rigid plastic packaging collected from Copenhagen indicates actual plastic recycling rates from full scale facilities as low as 33-43%, with the remainder exported as mixed plastic to low grade uses, a very small amount of metals and a significant residual fraction (29-53%) as refuse derived fuel (RDF).[171] Regarding flexible plastics, reprocessors in the UK report that virtually all of the material collected in the UK is exported abroad for re-processing in countries outside the EU.

Of these streams resulting from the re-processing of plastics, the RDF stream is not thought to be sensitive to any PAC plastic content.[172] However, the fate and impact of

[171] Plastic ZERO (2014) *Comparative Assessment of Five Tested Sorting Facilities*, August 2014, http://www.plastic-zero.com/media/60120/4_4_comparative_assessment_of_the_tested_technologies_august_2014_final.pd

[172] Tonjes, D.J., and Greene, K.L. (2013) *Degradable Plastics and Solid Waste Management Systems*, November 2013, http://www.stonybrook.edu/est/people/documents/Degradable%20Plastics.pdf

PAC plastic content in plastics recycled both to high grade uses (recycled PET etc.) and to lower grade ones (mixed polymer products) warrants detailed investigation.

For plastic films and flexible packaging (of particular interest due to the PAC plastic market's focus on plastic bags), there are additional barriers that are yet to be fully overcome. In conventional recycling systems it has been important to keep flexible material separate from rigid plastics. Flexible packaging materials (films and plastic carrier bags) are difficult to separate mechanically and often result in low grade plastic bales being produced.[173]

Where film reprocessing facilities exist in Europe, these are predominantly dedicated to agricultural or commercial and industrial (C&I) films which tend to be thicker, made with one polymer, and are relatively clean.[174] However, systems are starting to emerge where household films are shredded, cleaned and re-extruded for use in end product manufacture. These systems can deal with paper and food contamination such as fats and oils, but pro-oxidant additives would be expected to remain in the extruded product (pellet or sheet / film). The potential applications for recycled films are reduced should there be any significant proportion of PAC polymer within the feedstock, as identified in a recent guide from WRAP , the UK 'Waste & Resources Action Programme':

> *"an oxo-degradable product feedstock is not appropriate for recycling into applications that require ongoing structural integrity within open environments, e.g. pipe work or damp proof membranes."*[175]

However, there may be better potential for an acceptable outcome if PAC plastic is kept separate from mixed plastic streams, as noted in the WRAP household film recycling guide:

> *"Mechanical recycling is technically feasible for some biodegradable and oxo-degradable plastics where these streams are kept separate from the conventional plastic stream, however, this does not happen at present because volumes are too low to make recovery economic."*[176]

Should it not be considered possible to identify PAC plastic within automatic sorting technology, then the situation of mixed but otherwise single polymer feedstocks has to be considered. As investigated within the first subsection below, we firstly attempt to

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[173] Plastic ZERO (2013) *Action 4.1: Market Conditions for Plastic Recycling*, January 2013, http://www.plastic-zero.com/media/60120/4_4_comparative_assessment_of_the_tested_technologies_august_2014_final.pdf

[174] AMEC Environment & Infrastructure UK, and Axion Consulting (2013) *Collection and Recycling of Household Plastic Film Packaging: A Review of the Current Status of the Household Plastic Film Packaging Recycling Supply Chain, Incorporating Collection Options and Emerging Markets*, Report for Waste & Resources Action Programme, 2013, http://www.wrap.org.uk/sites/files/wrap/MST1445_Plastic_Film_Breifing_Note_final%20for%20web.pdf

[175] Ibid.

[176] Ibid.

establish the possibility of sorting PAC plastic from conventional plastic and, secondly, we assess the recyclability of the PAC plastic based on results of technical tests.

It is worth noting that the PAC plastic industry asserts that their products are fully compatible with the existing plastics reprocessing industry. A number of studies have been commissioned by the industry which – at least partially – support their assertions. Similarly, the plastics reprocessing industry, both in the USA and Europe, has also commissioned studies which support their view that PAC plastics are incompatible with recycling processes and should not be present within their feedstock resins. The US-based Association of Postconsumer Plastic Recyclers (APR) states the following, which appears to be typical of the approach of the rest of the industry.

> *"APR's position is that suppliers of degradable additives have the burden of showing that their materials have 'drop in replacement' compatibility for the recycling process and for the next application with postconsumer polyethylene (HDPE and LDPE) and polypropylene (PP) not containing the degradable additives. This includes safety considerations, performance, materials, handling equipment needs, and maintaining yields and processing conditions."*[177]

Fully independent literature, i.e. not funded by either industry, has been difficult to find throughout this study.

Finally, we should note that we have only considered mechanical recycling as an option for PAC plastic. Although chemical recycling might technically be feasible, the market in Europe is too immature for this to be considered a viable alternative at present.

[177] The Association of Postconsumer Plastic Recyclers (2012) *Degradable Additives and Polyethylene and Polypropylene Recycling Technical Compatibility Testing Guidance*, January 2012, http://www.plasticsrecycling.org/images/pdf/PE_PP_Resins/Specific-Tests-for-PE-PP-Innovators/testing_degradable_additives_pe_pp.pdf

4.3.1 Hypothesis 9: PAC plastic can be identified and separated in collection systems.

The first question to consider is whether PAC plastic can be identified and treated as a separate waste stream; therefore preventing the material from entering the recycling process and mixing with regular plastics. If so, this will mean that the question of the compatibility of PAC plastic with recycling processes might consider PAC plastic as a single uniform stream (though for this to happen in practice would also require for a bespoke collection of PAC plastics to be operationally and economically viable).

Literature on this subject is limited, with the majority of studies looking at recyclability of PAC plastic assuming, explicitly or implicitly, that PAC plastic cannot be separated from regular plastic, whether within the collection systems or in the recycling process.

Separation within collection systems would have to be done manually, either by those discarding the waste (whether commercial, industrial or individual consumers) or by workers in collection systems, such as those on kerbside sort recycling rounds. For either group, key to being able to separate the PAC plastic from regular plastic is clear labelling, as PAC plastic is indistinguishable from conventional plastic. There are currently no standards for labelling of PAC plastic to enable such separation to occur—indeed, the industry itself, when defending against accusations that their product will be littered more often (see Section 4.2.2), asserts that there is no way to tell the difference between PAC plastic and conventional plastic without the use of identifying marks.

Where separation of PAC plastic – or other unconventional types of plastic – has been discussed in literature, this has only been briefly mentioned. WRAP, for example, states that enabling householders to differentiate between different plastics presents a *"considerable communications challenge"*.[178]

4.3.1.1 Conclusion

Hypothesis 9: "PAC plastic can be identified and separated in collection systems."
Refuted. The evidence does not support the hypothesis.
The evidence available does not support the postulation that PAC plastic can be identified and sorted separately by consumers since PAC plastic is identical in appearance to conventional plastic. With no standard labelling convention, there is also currently no way to reliably mark PAC plastic in the same way globally. Furthermore, there is no evidence that workers in waste collection systems would

[178] AMEC Environment & Infrastructure UK, and Axion Consulting (2013) *Collection and Recycling of Household Plastic Film Packaging: A Review of the Current Status of the Household Plastic Film Packaging Recycling Supply Chain, Incorporating Collection Options and Emerging Markets*, Report for Waste & Resources Action Programme, 2013, http://www.wrap.org.uk/sites/files/wrap/MST1445_Plastic_Film_Breifing_Note_final%20for%20web.pdf

realistically be able to separate PAC plastic from other plastic in an economically feasible way, nor is there evidence that might promote the concept of an economically viable separate dedicated collection system for PAC plastic. For such approaches to be achieved in practice would require a paradigm shift in both packaging design (or standardised labelling) and also in waste collection systems.

4.3.2 Hypothesis 10: PAC plastic can be identified and separated within recycling processes.

As per the previous hypothesis, this hypothesis postulates that PAC plastic can be separated and thus treated as a separate waste stream from conventional plastics. In this case, the focus is further downstream from collection during the recycling process itself. Separation during the recycling process of PAC plastic mixed with conventional plastic would require either a mechanical technique or manual sorting. As explained in Section 4.3, most reprocessors in Europe currently separate rigid plastics by detecting different properties of plastics using NIR separation technology. This technology cannot currently detect PAC plastic.

Evidence relating to this hypothesis is also limited in literature, although a North Carolina Department of Environment and Natural Resources report from 2013 states:

> *"The automatic sorting machines used by the plastics recycling industry cannot detect normally durable plastics rendered degradable by additives. The machines seek the spectroscopic signature of the plastic and will see packaging with and without the additives as the same."*[179]

This report is based on interviews with reprocessors based in North Carolina, USA. Our own interviews with reprocessors and their representative trade associations conducted during the course of the current study also corroborate the above, namely that in Europe, it is also not possible to mechanically sort the PAC plastic from other plastic. This is further confirmed by evidence provided to the UK Environmental Audit Committee's report on plastic bags, when an exemption for the upcoming plastic bag charge in England was considered for biodegradable bags. The evidence provided by one reprocessor was based on a conversation with a manufacturer of the sorting technology, who confirmed that their technology could not distinguish between PAC plastic and regular plastic.[180]

Regarding plastic films, evidence from reprocessors states that the hourly tonnages of material processed by these plants make manual sorting of these materials economically unviable. This assumes that the films are readily identifiable, which is currently not the case, as concluded in the previous hypothesis.

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[179] North Carolina Department of Environment and Natural Resources (2013) *Study on the Effects of Degradable Plastic on Recycled Feedstocks*, Report for North Carolina State Legislature - Environmental Review Commission, January 2013, http://www.ncleg.net/documentsites/committees/ERC/ERC%20Reports%20Received/2013/Department%20of%20Environment%20and%20Natural%20Resources/2013-Jan%20Degradable%20Plastics%20Recycled%20Feedstocks%20Rpt.pdf

[180] Environmental Audit Committee (2014) *Environmental Audit Committee - Eleventh Report: Plastic bags*, January 2014, http://www.publications.parliament.uk/pa/cm201314/cmselect/cmenvaud/861/86102.htm

4.3.2.1 Conclusion

Hypothesis 10: *"PAC plastic can be identified and separated within recycling processes."*
Refuted. The evidence does not support the hypothesis
The evidence available does not support the postulation that PAC plastic can be identified and sorted separately by reprocessors with the technology that is currently available.

4.3.3 Hypothesis 11: The quality of conventional plastics recyclate is not negatively affected by PAC plastic added to the feedstock.

Within this hypothesis, we have explored whether there are negative impacts on the resulting recyclate if PAC plastic enters the recycling process alongside conventional plastic – whether this be LDPE, HDPE, PS or PP. As stated earlier, we have attempted to find evidence to suggest that compatibility with recycling processes may depend on the intended use of the resulting recyclate. Furthermore, the hypothesis also postulates that any potential negative effects on recyclate can be mitigated by stabilising additives (anti-oxidants) added during the recycling process.

It is worth noting initially that we are only aware of one set of guidance that provides a mechanism for testing the recyclability of PAC plastic.[181] This is the APR's *"Degradable Additives and Polyethylene and Polypropylene Recycling, Technical Compatibility Testing Guidance."*[182] This document has been developed in conjunction with reprocessors and suggests a set of tests to assess the durability and impact on physical properties when conventional HDPE, LDPE and PP are mixed with PAC plastic and used as feedstock for a recycling process. Different tests are proposed depending on the end-product that is simulated. For example, tests for injection moulding and extruded lumber require both that bales of initially extruded sheet are aged for the equivalent of eight months before being made into bars. These are then aged for the equivalent of 100 years before their physical characteristics are tested. The guidance does not propose that stabilisers are added at any stage to counteract the activity of the prodegradant additives. We are not aware of any published tests that have been carried out following this guidance.

In the following section, we present the key studies that present empirical data on recyclability of PAC plastic, as well as any relevant published criticism of these.

A 2007 study by the Centre de Recherche Industrielle Québec (CRIQ) produced on behalf of the regional state agency RECYC-QUÉBEC considered the compatibility of recycling different types of PAC plastic (although referred to as "biodegradable" in the study) bags in different percent mixtures.[183] This includes two types of PAC plastic bags: "NeoSac" and "EPI". The methodology and results appear to generally be accepted by the industrial community; we are not aware of any significant concerns raised with the study. The report concludes as follows:

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[181] DEFRA (2015) *Review of Standards for Biodegradable Plastic Carrier Bags*, December 2015

[182] The Association of Postconsumer Plastic Recyclers (2012) *Degradable Additives and Polyethylene and Polypropylene Recycling Technical Compatibility Testing Guidance*, January 2012, http://www.plasticsrecycling.org/images/pdf/PE_PP_Resins/Specific-Tests-for-PE-PP-Innovators/testing_degradable_additives_pe_pp.pdf

[183] Centre de Recherche Industrielle Québec (CRIQ) (2007) *Evaluation of the Impact of Biodegradable Bags on the Recycling of Traditional Plastic Bags*, Report for Recyc-Québec, August 2007

"Oxo-biodegradable bags "NeoSac" and "EPI" showed excellent compatibility with traditional bags during the preparation of mixtures and during extrusion of profiles and films. However, the films obtained from mixtures of "NeoSac" bags and traditional bags showed a rapid and considerable degradation after only a few days of accelerated aging. Bags from these cannot be considered as being perfectly compatible with the traditional plastic bag recycle stream.

The "EPI" oxo-biodegradable bags can be considered as being compatible with the traditional plastic bag recycling stream, because of the results obtained during the preparation of mixtures and during the extrusion of profiles and films as well as the initial performance of profiles and films and the performance of these following accelerated aging."

These results have led to two different interpretations, with the PAC plastic industry claiming that the results show compatibility with the 'right' kind of PAC plastic bag and others, notably the Loughborough University LCA report[184], suggesting that it shows an overall incompatibility. The PAC plastic industry has suggested that the different results could suggest that the NeoSac had already partially degraded at the time of entering the recycling process or that it was simply a lower quality material. Regardless of which of these theories is correct, the results do suggest clearly that at a very basic level, at least with some type of PAC plastic recycled under some specific conditions, it is possible that particularly poor quality recyclate will be produced. Equally, it also appears possible to produce high quality recyclate. Nonetheless, there is no way of telling how PAC plastic collected for recycling will perform in the recycling process since there are no standards or minimum requirements for materials placed on the market, nor is it possible to control what environmental conditions the plastic may have been exposed to in use.

Another key finding of this report is that PAC plastic that had been exposed to *"UV rays in a hot and humid atmosphere*" were found to reduce the quality of recyclate significantly (signified by a reduction in mechanical performance); in one instance with as little as four days' intensified exposure. The accelerated ageing was performed to ASTM D5208[185]. This test specifies 20 hours of UV exposure at 50°C followed by four hours of 100% humidity at 40°C during each 24 hour period that the sample is on test. Whilst the study does not provide an equivalent timescale for natural aging, indications provided in Section 4.1.1 suggest that a 24 hour accelerated aging period might equate to around 24 days in real life—suggesting around 100 days of real life aging for four days' worth of accelerated aging. This suggests that in some instances very little natural UV exposure is necessary for PAC plastic to become degraded to the point in which it cannot effectively be recycled. Although the PAC plastics industry maintain that their products can be 'programmed' using different concentrations and additive formulations, there is

[184] Loughborough University (2010) *Assessing the Environmental Impacts of Oxo-degradable Plastics Across Their Life Cycle*, Report for Defra, January 2010

[185] ASTM D5208; Standard Practice for Fluorescent Ultraviolet (UV) Exposure of Photodegradable Plastics

no way of controlling the time spent between manufacture and disposal. Equally, the level of UV exposure cannot be guaranteed.

A California State University report from 2007, commissioned by the California Integrated Waste Management Board, assessed the performance of a variety of "degradable" plastics, including a mixture of LDPE with both 10% and 20% "oxodegradable plastic" contamination.[186] The results showed that the melt index of the mixture was reduced by the presence of the "oxodegradable" contamination (by 16% for the 10% mixture and 6.6% for the 20% mixture), however the researchers urged further investigation as the results were not consistent: the higher level of contamination provided a lower impact on the melt index. Furthermore, both the tensile modulus and the elongation at break increased with the contamination from PAC plastics, however, this was as a result of different LDPE formulations, i.e. the base polymer, in the two materials.

A 2012 report by the South African Roediger Agencies commissioned by the PAC plastics industry concludes that d2w containing plastic (manufactured by Symphony Environmental) can be mixed with conventional plastic film with no detriment to products made with the recyclate.[187] Mixtures of PAC plastic and recycled waste LDPE in ratios of 90:10 to 50:50 were created and subjected to either accelerated UV aging or heat aging. Similar to the CRIQ study, UV aging was performed in accordance with ASTM D5208. In this case, however, an outdoor exposure equivalent was proposed with 400 hours equalling one year in South Africa. This is broadly in line with other proposals that 1 hour accelerated exposure = 1 day natural exposure.

As has already been identified in the biodegradation testing literature, heat exposure without UV does not accelerate the abiotic degradation process significantly. This was also one of the findings in the Roediger study; heat ageing produced comparatively little change in the tensile strength of the test samples compared with samples treated with UV over the same period of time. This demonstrates that correct storage of the recycled material i.e. in cool dark atmospheres, can preserve qualities of PAC plastic containing recyclate. However, both the heat and UV aging tests of the Roediger study were performed on samples that were 'recycled' (blown into film and then re-pelletised) in-house from primary materials rather than from recovered post-consumer waste material. Therefore, this does not demonstrate the effects of any oxidation as a result of UV ageing that has occurred during use, and/or between disposal and being recycled. By nature of real world situations involving an open system, where the environmental conditions and time spent prior to reprocessing cannot conceivably be fully controlled, it

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[186] California State University (2007) *Performance Evaluation of Environmentally Degradable Plastic Packaging and Disposable Food Service Ware - Final Report*, Report for California Integrated Waste Management Board, June 2007

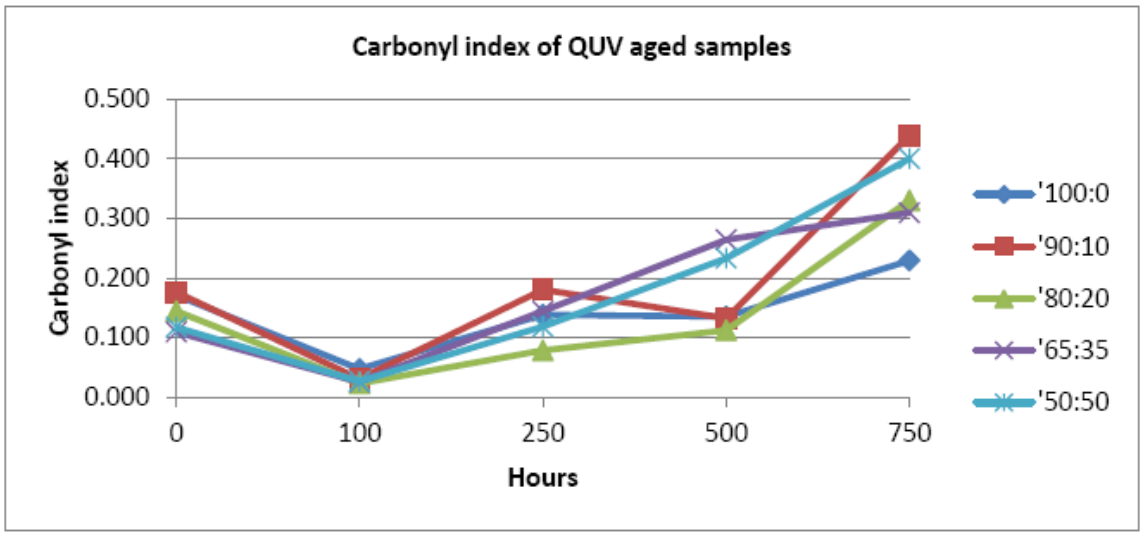
[187] Roediger Agencies (2012) *Recycling Report on d2w Oxo-Biodegradable Plastics*, Report for Oxo-biodegradable Plastics Association, May 2012, http://www.biodeg.org/ROEDIGER%20REPORT%2021%20May%202012.pdf

is resultantly not possible to control the level of oxidation in post-consumer PAC plastic recyclate.

Looking further into the results of the Roediger study, whilst the results also show that UV degradation reduces the tensile strength of LDPE both when it is on its own and when mixed with PAC plastic, this does not necessarily indicate a change in molecular weight. As has already been indicated, oxidation of PAC plastic can lead to lower molecular weight; however, for practical reasons the MW was not measured, only the carbonyl index was. The results of this are conflicting (see Figure 23) as although the lowest carbonyl index is found in the pure LDPE (100:0), the highest is found with the next lowest level of PAC plastic proportion (90:10). Despite this discrepancy—which is not commented upon or explained in the study—the addition of PAC plastic to the mixture appears to have a detrimental effect.

When stabilisers were added, mixtures of up to 25% PAC plastic were found to have no impact on outdoor life expectancy after the equivalent of 24 months outdoor exposure. The researchers therefore conclude that stabilisers should be added in order to achieve this effect for products with a desired longer lifetime. The report also suggests that the stabilisers should be added by the re-manufacturers, not the reprocessors, as they can tailor the stabiliser to the required lifetime and use of the product. Furthermore, the report argues that the many standards for long-life products require that any products made with recyclate come from a known origin, and that the argument against PAC plastics that is concerned with the uncertainty of the origin and composition of the feedstock is therefore not relevant to these products.

Figure 23: Carbonyl Index of UV Aged Samples with Varying Proportions of PAC Plastic



Source: Roediger Agencies (2012)

A 2016 report by the Austrian Transfercenter für Kunststofftechnik (TCKT), which appears also to have been commissioned by the PAC plastics industry, concludes that the

shelf life of recyclates containing PAC plastic is compatible with producing short-life products from such recyclates.[188]

This report found a shelf life of one year is possible from films that have been exposed to accelerated heat aging (with no UV exposure) for 640 hours, with mixtures containing between 5% and 75% PAC plastic, and two years for mixtures containing 100% PAC plastic stored for 640 hours in accelerated heat aging. The authors state that the increase in shelf life for the product containing 100% PAC plastic material is likely a result of the "stabiliser package" that forms part of that particular additive (Symphony's d2w).

It is difficult to give weight to the conclusions of the TCKT study given concerns about the results in terms of unclear trends between the different percentage mixtures, a lack of UV light exposure, and a lack of information about whether any prior oxidation of the d2w-containing material has happened and what the storage conditions of the films were like ahead of entering the recycling process.

Jackubowicz and Enebro[189] also studied the reduction in elongation at break of various mixtures of PAC plastic with conventional LDPE, in both stabilised and unstabilised form, using heat aging. No indication of a conversion factor between time in heat aging to time in regular use was provided in their article, though the formula used to estimate the service life indicates a conversion factor of around 87 from the time in heat aging to time of the product in regular use. Stabilised samples were heat aged for up to more than 200 days [presumed equivalent to around 50 years], while non-stabilised samples were heat aged for up to 55 days [presumed equivalent to around 13 years]. Mixtures of both 10% and 20% PAC plastic material were studied, as well as a pre-oxidised 10% PAC plastic sample (to around 30% of elongation at break). This latter sample was intended to show the impact of using PAC plastic material where the oxidation process has already commenced prior to the material entering the recycling process.

The results showed change in the elongation at break for the majority of samples compared to the control materials (no PAC plastic). The researchers used the results to estimate the resulting 'service' life of the materials. Their results for the stabilised materials are outlined in Table 11.

[188] Transfercenter für Kunststofftechnik (TCKT) (2016) *Effect of Mechanical Recycling on the Properties of Films Containing Oxo-Biodegradable Additive*, March 2016

[189] Jakubowicz, I., and Enebro, J. (2012) Effects of Reprocessing of Oxobiodegradable and Non-degradable Polyethylene on the Durability of Recycled Materials, *Polymer Degradation and Stability*, Vol.97, No.3, pp.316–321

Table 11: Estimated Service Life of Stabilised Materials

Sample	PAC plastic	Composition	Estimated service life
Test 1	P-Life (manganese salt)	10% additive	>50 years
Test 2	P-life	20% additive	>15 years
Test 3	P-life	10% pre-oxidised additive	16 years
Test 4	Nor-X (iron salt)	10% additive	18 years
Test 5	Nor-X	20% additive	~10 years
Test 6	Nor-X	10% pre-oxidised additive	3.5 years
Control	-	0%	>50 years

Source: adapted from Jakubowicz, Enebro (2012)

These results show that there is a decrease in service life for almost all materials, and that the estimated service life depends largely on the additive used, the percentage of the mixture, whether stabilisers are added or not and whether the PAC plastic has been oxidised prior to entering the recycling process. A key improvement over the Roediger study is the investigation of pre-oxidised samples. In this case the estimated service life was reduced by 3—5 times and is a more likely scenario than PAC plastic reaching the recycling process with no evidence of oxidation. Importantly, this reduction is also based on the use of an anti-oxidant stabiliser in all samples—notably at a lower concentration than the Roediger study; 0.1% compared with 0.16%.

The study concluded that;

> *"…stabilizer content is a crucial factor for the thermo-oxidative stability of plastic mixtures containing OBD [PAC] materials."*

As the researchers note, both in this paper and in others, the concentrations of additives used in the study, from 10% upwards, are much higher than the current market penetration levels of PAC plastic in the UK and Europe. These results should therefore be seen as a picture of the potential impact of recycling PAC plastic in a situation where the market has increased significantly in size.

In addition to the empirical studies, a number of literature reviews over the past fifteen years have attempted to assess the literature on the impact of PAC plastics on recyclates, although conclusions vary between reports.

For example, Tonjes and Greene (Stony Brook University, USA) concluded in 2013 that degradable plastics, which in this study includes both bio-based and PAC plastics, *"can be considered to be recyclable, as they constitute only a very small part of overall feedstock, not enough to make a measurable impact given other concerns in recycling plastics".* This is despite referencing the 2007 California State University study which finds a reduction

in particular physical properties,[190] and both the 2012 summary of Thomas' 2010 LCA of plastic carrier bags for Defra,[191] and the 2003 Australian ExcelPlas et al. LCA study on plastic carrier bags,[192] all of which are critical of the potential for PAC plastic to be recycled with conventional plastics.

For example, the final response to industry from the authors of Defra's plastic carrier bag LCA concludes that:

> *"Oxo-degradable plastics are not suitable for recycling with main-stream plastics. The recyclate 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."*[193]

This conclusion is based on an interpretation of the 2007 CRIQ study discussed earlier.

The ExcelPlas et al. study from 2003, commissioned by the Australian Department of the Environment and Heritage, concludes that:

> *"degradable plastics have the potential to interfere with the processing of recovered polymers and to destabilize and compromise the properties of recycled polymers if they enter the plastics recycling stream"* [194]

This is based on consideration of limited scientific evidence available at the time. In fact, the only study that ExcelPlas references is a study by Eyenga et al. from 2001 which looked at the Degrade additive, an anti-oxidant. This was reported to find "virtually no impact" on the Melt Flow Index after the resin had been processed five times through an extruder. The ExcelPlas study also comments that prodegradants can destabilise resulting recyclate products and that any problems might not be detected until after fabrication of the materials. Finally, the study also states that the impact of metal ion *can* be mitigated by using chelating additives that bind the ions. And this can *"largely offset"* the impact of the prodegradants. It is not clear whether any accelerated aging or heating techniques had been used by the researchers.

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[190] California State University (2007) *Performance Evaluation of Environmentally Degradable Plastic Packaging and Disposable Food Service Ware - Final Report*, Report for California Integrated Waste Management Board, June 2007

[191] Thomas, N.L. (2012) Oxo-degradable Plastics: Degradation, Environmental Impact and Recycling, *Proceedings of the Institution of Civil Engineers*, Vol.165, No.3, p.133

[192] ExcelPlas Australia, Centre for Design at RMIT, and Nolan-ITU (2003) *The Impacts of Degradable Plastic Bags in Australia*, Report for Department of the Environment and Heritage (Australia), 2003

[193] See the authors response to industry criticism of: Loughborough University (2010) *Assessing the Environmental Impacts of Oxo-degradable Plastics Across Their Life Cycle*, Report for Defra, January 2010

[194] ExcelPlas Australia, Centre for Design at RMIT, and Nolan-ITU (2003) *The Impacts of Degradable Plastic Bags in Australia*, Report for Department of the Environment and Heritage (Australia), 2003

Other recent studies include a literature review and stakeholder engagement project by the North Carolina Department of Environment and Natural Resources from 2013.[195] This study is mainly based on interviews with reprocessors and manufacturers of recycled plastic products. The interviewees express concern about the *potential* impact of PAC plastic in their recyclate and the impact this might have on the quality and functionality of the final product and the resulting commercial implications. No specific data is presented for either side of the argument. The lack of data from the PAC plastic industry is listed as one of the key reasons for concerns among the reprocessors.

4.3.3.1 Conclusion

4.3.3 Hypothesis 11: "The quality of conventional plastics recyclate is not negatively affected by PAC plastic added to the feedstock."
Refuted. The evidence suggests there can be no guarantee of avoiding negative effects by introducing PAC plastic into recycling streams.
The evidence, although varying in nature and in conclusions, and in whether it has been independently commissioned by industry, does not allow for this hypothesis to be supported when considered in context of real life production, consumption and waste systems. It is not disputed that the exact concentration and formulation of the PAC plastic and stabiliser package in recycling feedstock will have an impact on the final recyclate. There is evidence that supports the proposition that with precise formulation, appropriate storage of the PAC plastic before recycling, and the addition of stabilisers, it is possible to produce a feedstock that will not have negative quality impacts in comparison to a pure conventional plastic alternative. The practicalities of being able to guarantee precise formulation are however questionable; there are currently no known systems in place to properly understand the levels of PAC plastic being placed on various markets, and hence what level of PAC plastic may feature in materials collected for recycling. Furthermore, recycled material can conceivably come back as an end-of-life product for recycling any number of times, thus compounding the multifariousness of the chemical content of recycled polymers. The lifetime or shelf life of this feedstock will depend again on the above properties of the PAC plastic entering the recycling process, but evidence suggests it may be possible to create a feedstock with a shelf life that is long enough for the production of short-life

[195] North Carolina Department of Environment and Natural Resources (2013) *Study on the Effects of Degradable Plastic on Recycled Feedstocks*, Report for North Carolina State Legislature - Environmental Review Commission, January 2013, http://www.ncleg.net/documentsites/committees/ERC/ERC%20Reports%20Received/2013/Department%20of%20Environment%20and%20Natural%20Resources/2013-Jan%20Degradable%20Plastics%20Recycled%20Feedstocks%20Rpt.pdf

materials such as bin liners and carrier bags. However, the evidence also suggests that without controls and stabilisers the recyclate produced may not be appropriate as feedstock at all, or that it may not be appropriate to use as feedstock after a particular period of aging. Evidence suggests that recycling of PAC plastic that has undergone oxidation can significantly impair the physical qualities and service life of the recycled product. The fact that it is impossible to fully control the level of aging experienced by PAC plastics during the product use phase, prior to products becoming waste and entering recycling processes, presents a major issue.

The practicalities of controlling these variables and identifying when and where it is appropriate to use the resulting recycled material are a significant barrier. Without a homogeneous material of known provenance, PAC plastic poses a significant risk to recyclers and product manufacturers.

4.3.4 Hypothesis 12: The presence of PAC plastics in recyclate does not affect recyclate prices or marketability.

As outlined previously, much of the feedstock for plastic film recycling involves international flows of material. However, within the remaining feedstock, UK reprocessors (considered as an example national situation in the European context) report that there is *currently* no direct impact on their business of PAC plastics in their feedstock. Although the amounts of PAC plastics in their feedstocks are not known, with the PAC plastics market being immature in the UK, this does not appear to affect the reprocessors at present. However, a European recycler and re-manufacturer of film plastics contacted in the course of this study stated:

> *"If there is a risk of [PAC] oxo plastic getting into the waste stream we would stop using recycled material, if this happens the market for recycled LDPE would be much reduced, prices would fall dramatically causing huge damage and a contraction of the plastic films recycling sector."*[196]

Anecdotally it has also been conveyed to the researchers for this study that UK-based reprocessors have been unable to sell their products due to fear of contamination from PAC plastics. One waste collector and primary material processor from the UK quoted that:

> *"…many of our end-market reprocessors do not like having [PAC] oxo-material in their load of recycled plastics. They claim their own customers refuse to accept reprocessed plastics if there is the likelihood of oxo-plastics in the product."*[197]

Jessica Baker who submitted evidence towards the UK Environmental Audit Committee on the subject of plastic bags in 2014[198] commented the following on behalf of Chase Plastics, a UK processor of recycled plastic:

> *"Because long-life and durable products are the staple end markets for reprocessed plastic, the entry of [PAC] oxo degradable products into the plastics waste stream in any quantity could not only destroy this market but also undermine the aspirations for a circular economy. [PAC] Oxo degradable plastic is a 'stealth' material that will slip through all collection and sorting stages of the reprocessing supply chain. Zero tolerance is the only way to protect reprocessed plastics and their end markets."* [199]

Although this information on its own is anecdotal and not supported by data (for which the reader is referred back to the previous hypothesis), it is also important to recognise

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[196] Personal contact with a European waste film recycling and re-manufacturing business.
[197] Personal contact with a waste collector and primary material processor from the UK.
[198] Environmental Audit Committee (2014) *Environmental Audit Committee - Eleventh Report: Plastic bags*, January 2014, http://www.publications.parliament.uk/pa/cm201314/cmselect/cmenvaud/861/86102.htm
[199] Personal contact with Jessica Baker, Chase Plastics.

that contact with reprocessors, as part of this study, did not give rise to any that were in support of PAC plastics in their recycling streams. It appears that any uncertainty in quality—of which there is much with regard to the recycling of PAC plastic—could result in a significant loss of faith in the recycled film market.

Within literature, we have also not been able to identify any studies that suggest to what degree off-takers of recyclates would be willing to accept any amount of PAC plastics in the recyclate they purchase.

However, as raised on numerous occasions by the re-processing industry, the problematic issue from their point of view is not so much the current scenario–where market penetration of PAC plastic is limited–but rather the *potential future* scenario in which the market size of PAC plastics has grown to such an extent that doubt begins to emerge as to the quality of the final feedstock. Reprocessors report that they expect, if this situation were to occur, that they would lose business, particularly from those end-users who produce long-life products where they must be able to guarantee specific properties for a certain lifetime. They expect that only those manufacturers who are less concerned with achieving a 'high quality' product will be willing to take on the risk of purchasing recyclate potentially containing PAC plastic and that others who are more risk-averse will cease manufacturing with recycled materials and revert to virgin materials. They believe that this will therefore reduce the size of the market for recyclates and inevitably reduce their prices as well. The PAC plastic industry states that any risk can be mitigated by the addition of stabilisers and that this would be best done by the manufacturers or end-users themselves, so they can be tailored to the product they are making. The reprocessors are concerned that no manufacturers will be willing to do this as it will represent an additional cost to them – which will then also be likely to be passed back to the reprocessors.

4.3.4.1 Conclusion

Hypothesis 12: The presence of PAC plastics in recyclate does not affect recyclate prices or marketability
Refuted. There is evidence that PAC plastic can affect marketability, and if PAC plastic is more widely used in future then it is likely that further issues will be experienced in this regard.
Clearly there is a direct read across between this hypothesis and the conclusions of the previous one. With potential negative impacts on the quality of recyclate containing PAC plastic, there is an inevitability that prices and markets for post-consumer recyclate which may contain PAC plastic will be affected. Concerning the current situation, reports from reprocessors are mixed at present, which reflects the low level of uptake of PAC plastic. Whilst in some cases it has been reported that there is no current impact on marketability or prices of recyclates that can be traced to PAC plastic, equally there are incidents of material containing PAC plastic being refused.

At this current time, there is a distinct lack of data to support the hypothesis, and price differences are not likely to be made public. However, it is clear that there is a risk to recyclers and whether this risk is based upon a genuine or perceived issue in the recycling process is less important. Until such time as the recycling industry's fears can be allayed in that their processes and products will not be negatively affected, then they will continue to be cautious.

4.3.5 Hypothesis 13: The presence of PAC plastic in recyclate does not affect the ability of manufacturers to guarantee specific business requirements relating to physical properties (such as tensile strength etc.).

As per the evidence and discussions under the previous hypothesis, the levels of PAC plastic in use in Europe today do not appear to be affecting reprocessors' or manufacturers' ability to guarantee particular specifications or properties. However, the concern from the reprocessors' point of view is that they will be unable to guarantee particular properties in a future scenario where PAC plastics have a greater market share. As per the evidence provided under an earlier hypothesis in this section, PAC plastic present in the feedstock does have a significant potential to impact on the final recyclate, particularly if a variety of PAC plastics from a variety of sources are mixed into the feedstock.

Due to a lack of extensive test results and market information on PAC plastics, this report does not attempt to estimate at what stage this impact would be felt, i.e. what the market penetration level would need to be before reprocessors might be impacted.

4.3.5.1 Conclusion

Hypothesis 13: The presence of PAC plastic in recyclate does not affect the ability of manufacturers to guarantee specific business requirements relating to physical properties (such as tensile strength etc.).
Market dependent. In relation to the current situation where PAC plastic is thought to be very minor component of post-consumer waste, there are unlikely to be issues. However, if PAC plastic is more widely used in future it is possible that issues may arise.
Reprocessors have reported to us that currently no impact on physical properties (or the ability to guarantee these) can be traced to PAC plastic. However, due to the low levels of PAC plastic currently in the recycling feedstocks in Europe and a lack of data as to what exactly this level is, we are not able to confidently conclude whether such an impact could exist in a future scenario where the market of PAC plastic is notably larger.

4.4 Market Restrictions and Case Law

Where relevant, the scientific evidence associated with any country restrictions on PAC or conventional plastics has been incorporated into the discussions in the sections above. Here, we list the known, and more relevant rulings taken by particular nations and regions from around the world, and summarise the rationale behind the decision making from information where it was found to be available in the published sources. It should be noted that no warranty may be given as to the completeness or accuracy of the information provided since the countries in question were not contacted in the context of this review.

For the most part, very little scientific analysis is currently available upon which reliance has been placed by countries which have implemented policies in relation to PAC plastic. This is the case for both countries in favour of banning its use entirely, and those in favour of prohibiting the use of other plastics in favour of PAC plastic. Regarding those advocating its use, the commentary provided tends to be general in nature and assertions are made as though they have the status of fact without justification or reference to the source of information. Where laws are implemented banning plastics in the general sense, the basic principle of environmental protection is advanced as rationale for such a policy due to the level of plastic consumed, and issues associated with waste and litter.[200] Environmental protection is, however, also a commonly stated goal of policies mandating the use of PAC plastic. Regarding the two identified cases advocating a ban specifically on the use of PAC plastic, the rationale given is the lack of compostability and failure to meet degradability standards.

[200] Larsen, J., and Venkova, S. (2014) *The Downfall of the Plastic Bag: A Global Picture*, accessed 1 June 2016, http://www.earth-policy.org/plan_b_updates/2014/update123

Table 12: Global Snapshot of Policies Relating to Degradable Plastic

Location	Policy Adopted / Ruling Taken	Stated Rationale (where evident)
UAE	Ban on various categories of plastic film products except those made from PAC plastic[201]	As a response to the issue of litter
Pakistan	Prohibition of non-degradable plastic products [carrier and garbage bags, agricultural film / mulching films]. PAC plastic is allowed[202]	To deal with plastic bag issue – presumed to relate to litter
Yemen	Mandatory use of PAC plastic in plastic bags[203, 204]	To promote the use of "environmentally friendly plastic bags"
Philippines	Mandatory [205]	To prevent marine pollution
Morocco	Mandatory [206]	
Singapore?	Mandatory (not verified)	Environmental protection
DR Congo	Ban (proposed)[207]	Prevent environmental pollution
Rwanda	Ban – on non-biodegradable plastic bags [208]	Avoidance of use of plastic
France	Ban on all lightweight plastic carrier bags, including PAC, and excluding bags that are biodegradable in home composting systems, from July 2016[209]	Environmental protection and to reduce plastic dumped at sea
Canada – Montreal	Ban – on all carrier bags including PAC from 2018[210]	Reinforcing the shift to a greener city
California	Ban – on retailers giving out free plastic bags to consumers (challenged - referendum to take place in November 2016)[211]. Also prohibition of plastic bags labelled with the terms "biodegradable," "degradable," or "decomposable," or any form of these terms or with a logo indicating biodegradability. Sale of plastic bags labelled as "compostable" or "marine degradable" may be allowed provided they meet the ASTM standard specifications.[212]	Prevention of pollution associated with plastic
Italy	Ban on all plastic bags, including PAC, but with exemption for biodegradable bags under EN 13432 [213]	To reduce consumption of plastic
Belgium (Walloon Region)	Ban (proposed)[214]	Reduce use of plastic bags by consumers
Iran, Balkan states, 'some African countries'	Passed laws which state consumer plastics must be PAC.[215]	Various reasons advanced – ability to degrade etc.

UK	Ban on the ploughing in of degradable mulch films [216]	Non-compostability of the films

4.4.1 Policies Advocating the Use of PAC Plastics

In countries where legislation has been introduced to ban plastic products unless comprised of PAC plastic, for example in some Middle Eastern countries, the rationale behind such an introduction is stated to be based on environmental concerns. However, as part of this current review, efforts made to identify the scientific evidence base that may have been presented to inform national decision making processes have been unsuccessful.

In Pakistan, it has been argued that a conversion to PAC plastic bags will offer a solution to the extremely high consumption of plastic bags as this type will degrade and therefore prevent the huge level of plastic that currently arises with the use of ordinary plastic bags and the associated problem of littering. We have not been able to identify what

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[201] UAE standard 5009:2009, http://www.puntofocal.gov.ar/notific_otros_miembros/are53_t.pdf

[202] http://www.mocc.gov.pk/gop/index.php?q=aHR0cDovLzE5Mi4xNjguNzAuMTM2L21vY2xjL3VzZXJmaWxlczEvZmlsZS9GaW5hbCUyMFJlcG9ydCUyME1PQ0MlMjAtMiUyMHllYXJzLSUyMDA1XzEwXzIwMTUlMjAoMSkucGRm

[203] http://www.labelsandlabeling.com/news/latest/pakistan-moves-ban-non-degradable-plastic-products

[204] http://www.yementimes.com/en/1805/health/4171/Plastic-bags-feeble-laws-and-a-silent-threat-to-the-environment.htm

[205] Degradable Plastic Bag Act of 2011 (here: http://congress.gov.ph/download/basic_15/HB04055.pdf#page=4&zoom=auto,-266,720)

[206] Degradable Plastic Bag Act of 2011 (here: http://congress.gov.ph/download/basic_15/HB04055.pdf#page=4&zoom=auto,-266,720)

[207] http://www.zmescience.com/ecology/environmental-issues/congo-bans-plastic-bags-321313/

[208] http://www.rema.gov.rw/index.php?id=161

[209] http://resource.co/article/french-carrier-bag-ban-boost-bio-based-products-10988

[210] http://www.cbc.ca/news/canada/montreal/denis-coderre-plastic-bag-ban-future-montreal-1.3458240

[211] http://money.cnn.com/2015/02/25/news/california-plastic-bag-ban-delay/

[212] http://www.packaginglaw.com/ask-an-attorney/use-oxo-biodegradable-logo-plastic-bags-allowed-california

[213] http://www.plasticstoday.com/eu-finally-gets-serious-about-slashing-plastic-bag-use-balks-oxo-degradable-ban/73971415721529

[214] http://www.articlesfactory.com/articles/environment/policies-and-implementations-of-reusable-bags.html

[215] http://www.bakeryandsnacks.com/Processing-Packaging/Symphony-and-European-Bioplastics-clash-on-oxo-biodegradable-plastic

[216] http://www.packagingnews.co.uk/news/environment/oxo-degradable-plastics-should-be-incinerated-says-government-download-report-12-03-2010

scientific analysis may have been put forward in support of the case of PAC plastics here. It would appear that that regulation was introduced following meetings and discussion with industry groups.[217] As acknowledged in the associated press, there is no mechanism to test the *"environmental-friendly"* claims of such products.[218]

Likewise, in the United Arab Emirates where film based plastic products must also contain PAC plastic from suppliers audited by the Emirates Authority for Standardisation and Metrology, arguments put forward in favour of its use argue that it will help to protect the country's environment and protect animal and plant life from the effects of littered plastic at land and sea.[219] We have not been able to identify what evidence was considered in the debates that led to this law, although an unidentified study by the UAE's Ministry of Environment and Water is reported to state that half of all camel deaths in the UAE are due to camels ingesting plastic bags.[220]

Yemen is another country where plastic bags are mandated to be of PAC plastic. However, the cabinet decision obligating bag manufacturers to use PAC plastic has been criticised for ineffective implementation planning, a lack of public awareness and subsequent violations of the law. A subsequent law was passed prohibiting sale or manufacture of non-PAC plastic bags, but again this has not been enforced and "illegal" plastic bags production and use is said to continue.[221]

Rwanda introduced a total ban on non-biodegradable plastic bags including food packaging in 2008, although in certain cases the Rwanda Environmental Management Authority is reported to authorise the use of a PAC plastic for packaging of food products which cannot be packaged in paper envelopes.[222]

The OPA reports that *"governments of the following countries carefully considered the effectiveness and safety of oxo-biodegradable technology before passing legislation which makes it mandatory to use the technology:- Pakistan, United Arab Emirates, Mauritius, Yemen, Iran, Serbia, Kosovo, Albania, and [parts of] Brazil".* [223] In researching available published information from these countries, no evidence that could be said to be scientific in nature was located. Furthermore, it is believed that the regulations in a number of these countries have been overturned, or subjected to review, or have been

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[217] Shahzad Anwar, The Express Tribune (2015) *Non-Degradable Products: Plastic Bags Posing Environmental Hazards*, accessed 1 June 2016, http://tribune.com.pk/story/828090/non-degradable-products-plastic-bags-posing-environmental-hazards/

[218] Ibid.

[219] Samir Salma, Gulf News (2013) *UAE Bans Non-Biodegradable Plastic Products*, accessed 1 June 2016, http://gulfnews.com/news/uae/environment/uae-bans-non-biodegradable-plastic-products-1.1153432

[220] http://m.arabianbusiness.com/uae-finalises-green-plan-ban-plastic-bags-399807.html

[221] http://www.yementimes.com/en/1805/health/4171/Plastic-bags-feeble-laws-and-a-silent-threat-to-the-environment.htm

[222] http://allafrica.com/stories/201410160361.html

[223] Oxo-Biodegradable Plastics Association (2015) *Plastic Bag Bans and Taxes*, accessed 1 June 2016, http://www.biodeg.org/PLASTIC%20BAG%20BANS%20AND%20TAXES%20%20new%20-%2015.5.15.pdf

ineffectively implemented. As such it is difficult to verify with certainty if the laws implementing such measures are still in place.

4.4.2 Policies Advocating a Ban on PAC Plastic as a Component Part of a General Ban on all Plastic

Many European countries have implemented a levy system in relation to the use of plastic bags by consumers.[224] Such levies typically do not differentiate between different types of plastics and are introduced with the aim of minimising the use of such plastic bags in general terms. Specific mention of PAC plastic is made in some countries, for example France where a ban on all lightweight plastic carrier bags, including oxo, came into force on 1 July 2016. Government officials have highlighted the level of waste plastic dumped at sea as one of the main reasons for seeking such a ban.[225] The Walloon region of Belgium is set to implement a similar ban in 2017[226]and California is also considering a similar general ban[227], as is Canada from 2018[228]. China reportedly banned thin plastic bags in 2008, whereby use dropped by 40 billion bags a year.[229] In 2011, Italy passed a law banning the distribution of bags that are not reusable or are not made of non-biodegradable plastic (i.e. all plastics not complying with EN 13432, hence including PAC plastic in the ban) at shops and retail points.[230]

Primarily, the rationale for such blanket bans is to reduce the level of plastic consumed. It has been asserted in relation to many of these measures that the use of PAC plastic is not a proper alternative as it remains fundamentally comprised of ordinary plastic. Also, many reference the fact that its ability [and likelihood] to degrade has not been properly verified and as such it should be included in bans implemented to apply to all types of plastic. [231] [232]

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[224] Larsen, J., and Venkova, S. (2014) *The Downfall of the Plastic Bag: A Global Picture*, accessed 1 June 2016, http://www.earth-policy.org/plan_b_updates/2014/update123

[225] Agencia EFE (2015) *France to Ban Plastic Bags in Stores from Jan 2016*, accessed 1 June 2016, http://www.efe.com/efe/english/technology/france-to-ban-plastic-bags-in-stores-from-jan-2016/50000267-2710487#

[226] Bag to Green (2016) *The Environment is Suffering*, accessed 1 June 2016, http://www.bagtogreen.com/en_GB/page/lenvironnement-en-souffrance

[227] Morris, J., and Christensen, L. (2014) *An Evaluation of the Effects of California's Proposed Plastic Bag Ban*, 2014, http://reason.org/files/california_plastic_bag_ban.pdf

[228] René Bruemmer, Montreal Gazette (2016) *Montreal to Ban Single-Use Plastic Bags in 2018*, accessed 1 June 2016, http://montrealgazette.com/news/local-news/montreal-to-ban-plastic-bags-in-2018

[229] Pocono Record (2016) *Kicking the Plastic Bag Habit*, accessed 1 June 2016, http://www.poconorecord.com/article/20160512/OPINION/160519847

[230] The Grocery Box Company Ltd. (2016) *List by Country; 'Bag Charges, Taxes And Bans'*, accessed 1 June 2016, http://www.bigfatbags.co.uk/bans-taxes-charges-plastic-bags/

[231] Loughborough University (2010) *Research Questions the Environmental Credentials of 'Degradable' Plastics*, accessed 1 June 2016, http://www.lboro.ac.uk/service/publicity/news-releases/2010/52_degradable_plastics.html

[232] The Ecologist (2013) *Frontline Online: Plastic Not-So-Fantastic*, accessed 1 June 2016, http://www.theecologist.org/News/news_analysis/1814193/frontline_online_plastic_notsofantastic.html

The instrument introducing a charge on single use carrier bags in England includes provision for a review of industry standards for the biodegradability of certain lightweight plastic material to allow for the possibility for exclusion from the legal obligation. This review has now been completed but without being able to conclude that an exclusion would be warranted for certain types of carrier bags on grounds of biodegradability. The review cites issues that may arise for the plastic processing industry (as discussed in Section 4.3 above), as well as the lack of a standard specification that would ensure that plastic bags claiming to be biodegradable would biodegrade in all environments.[233]

4.4.3 Policies Advocating a Ban on PAC Plastic

In the case of agricultural mulch films, the Environment Agency in England prohibits un-degraded oxo-degradable plastics from being returned to the soil by ploughing in. As a result, all agricultural films in the UK are required to be removed from the land and recycled or disposed. Reasons given for the prohibition are the lack of compostability of PAC plastic[234] and *"because it is not considered beneficial or environmentally benign"*[235].

In California, according to public Resource Code Section 42357, the sale of plastic bags labelled as "biodegradable" or similar terms is prohibited. The terms "compostable" or "marine degradable" may only be allowed where the bags meet the ASTM standard. Due to the inability of PAC plastic to meet the ASTM standards, this effectively renders them unsaleable in California.

[233] DEFRA (2015) *Review of Standards for Biodegradable Plastic Carrier Bags*, December 2015
[234] Loughborough University (2010) *Assessing the Environmental Impacts of Oxo-degradable Plastics Across Their Life Cycle*, Report for Defra, January 2010
[235] Symphony Environmental (2010) *Response to Loughborough Report*, March 2010, http://www.biodeg.org/SYM%20RESPONSEto%20Loughboro%201.pdf

5.0 Summary and Recommendations

5.1 Summary

Concerning issues of biodegradability, from the available evidence within published literature and from stakeholder inputs, the following key conclusions can be drawn:

- The evidence suggests that PAC plastic is not suitable for any form of composting or Anaerobic Digestion process. Whilst PAC plastics industry sources also agree with this in an official capacity, we are aware of incidents where PAC plastic is marketed as suitable for these processes. PAC plastics are designed to degrade in much slower timeframes than are required for industrial composting and, therefore, there is a risk that fragmented plastics could be applied to land. In countries that have strict compost standards (such as the UK's PAS 100[236]) the output is strictly controlled and plastic fragments would invariably lead to a failure to meet these standards.
- The open environment is the unique selling point for the PAC plastics industry, which claims that their products biodegrade, and therefore, reduce impacts related to littering. Whilst the review of evidence undertaken for this report suggests that PAC plastic *can* biodegrade under certain circumstances, there is still doubt as to whether they *do so* fully or within reasonable time periods in practice. One finding that is clear is that PAC plastic is prohibited from biodegradation if it is not first exposed to UV radiation (and to a certain extent, heat) which breaks down the anti-oxidants and accelerates the oxidation process that is triggered by the pro-oxidant additives. This first abiotic stage of degradation prepares the PAC plastic for biodegradation by reducing the molecular weight of areas on the plastic surface to the point where it can be consumed by biological organisms, kick-starting the biotic degradation phase. This is the purpose of the pro-oxidant additive. If the circumstances for this to take place are absent (e.g. if UV exposure is only fleeting), biodegradation will either not take place (it will behave as a conventional plastic) or will be slowed significantly. This is the same for all environments.
- The degradation that occurs in landfill is primarily confined to the initial aerobic stage in the higher levels of the landfill. In the absence of oxygen (under anaerobic conditions of landfill operations), the PAC plastic is thought not to biodegrade. This makes PAC plastic marginally worse than

[236] BSI PAS 100: Compost specification, http://www.wrap.org.uk/content/bsi-pas-100-compost-specification-1

conventional plastic from a GHG point of view as it may lead to emissions of fossil CO_2 during the period where biodegradation takes place (if it does in practice to any meaningful degree).

- Biodegradation in the marine environment is another area where the PAC plastics industry claims their products offer improved performance relative to conventional plastics. There is very little evidence to suggest that timescales for biodegradation in the marine environment are significantly accelerated for PAC plastic compared to conventional plastic. Very few tests have been conducted, and whilst theories have been presented, biodegradation has not been practically demonstrated to take place in an accelerated timeframe.

Directly related to the issues of biodegradation are those of littering and how the PAC plastic will behave if it is littered, and thus what impacts should be expected:

- The potential toxic effects on soils of any residual additives have been identified as a concern by some commentators. Whilst it has not been conclusively proven that there are no negative effects, it does appear that the PAC plastics industry can create products that have minimal toxic impact on flora and fauna. This does not mean that all products on the market avoid negative toxic effects, as there is no regulatory control currently exercised in this regard. It is at least encouraging that almost all existing test standards for PAC plastic specify some form of toxicity test using established methods (such as germination and earthworm survival tests). However, problems remain that (a) accreditation is not mandatory for products on the EU market, (b) some of the standards do not have pass/fail criteria for the toxicological test results, and (c) there remains uncertainty surrounding real world toxicological impacts.
- The issue of whether a PAC plastic bag is more likely to be littered than a conventional plastic bag is one that is mired in speculation and spurious arguments. Such evidence as is available leans towards the hypothesis that there is a greater tendency for littering to occur if the user believes that the substance is 'biodegradable' (so that there might be counterproductive effects from marketing materials as such, where they have potential to create problems once littered). There are, however, two issues within this that first need to be separated:
    - Are the products marketed as biodegradable? And secondly,
    - Is the terminology confusing to consumers?

  The first question is often the defence of the PAC plastics industry as there is no noticeable physical difference between a PAC plastic bag (until it starts to fragment) and a conventional plastic bag. Whilst this argument is valid for bags that have no specific markings to differentiate them from one another, it is possible (indeed likely) that some form of marketing extolling the claimed benefits of PAC plastic products in this regard. Consequently, it may be that littering of PAC products is more likely because of claims regarding their

biodegradability. Nevertheless, rather than speculation, objective behavioural research is required to move this topic forward in a constructive manner.

- Concerning marine plastic litter, as has already been established there is no conclusive proof of PAC plastic degradation in the marine environment. It is the least aggressive of all the environments investigated in this report, but arguably, it is also the environment where the most damage could be done, and with the least chance of subsequently recovering the plastic. With PAC plastic being more likely to fragment than conventional plastic, to the extent that this occurs, it is less likely to be recovered during litter clean-up exercises, and will also likely be more easily mobilised. These factors can be reasoned to increase the chance of being transported into the marine environment.

  However, should full biodegradation on land occur, this would reduce the quantity that may otherwise transfer to the marine environment. It is not possible to conclude whether PAC plastic would increase or decrease absolute quantities of plastic in marine environments. Nonetheless, it seems likely that the fragmentation behaviour of PAC plastics will exacerbate issues related to microplastics.

  Working under the assumption that PAC plastic in marine environments will be more fragmented, the effect may be to reduce the impacts on wildlife in some respects (such as entanglement), but to increase the impacts in others (such as physical ingestion of microplastics). The PAC plastic is more likely to fragment quicker so the impacts associated with microplastics are concentrated within a shorter period of time—this could ultimately be worse than spreading out the impacts over a longer period of time due to an increase in the proportion of individuals, species and habitats affected, as well as the burden of impacts for an individual of a species. Although we are not able to provide conclusive judgement on marine issues, concerns remain that PAC plastics do not eliminate impacts, and also that impacts may be increased in certain important impact categories.

Concerning issues relating to the recycling of PAC plastics, the following key conclusions can be drawn:

- The evidence available does not support the suggestion that PAC plastic can be identified and sorted separately by reprocessors with the technology that is currently available. Furthermore, manual sorting would be time-consuming and is unlikely to be economically unviable–even in a hypothetical case where standardised labelling allows PAC plastics to be distinguished from conventional plastic. In the absence of market controls within any individual country, recycling of PAC plastic must therefore be considered in the context of a mixture with conventional plastic.
- There are significant concerns within the recycling industry that PAC plastic can negatively affect the quality of recycled plastic. Evidence suggests that

the impacts of prodegradant additives on recyclates can under certain circumstances be avoided with the inclusion of stabilisers. The appropriate quantity and chemistry of stabiliser would depend on the concentration and nature of the prodegradants in the feedstock. This presents significant issues, as the concentration of PAC plastic is often unknown and therefore it is difficult to know the correcting dosing. Furthermore, evidence suggests that oxidised PAC plastic can significantly impair the physical qualities and service life of the recycled product. The fact that it is impossible to fully control the level of aging experienced by PAC plastics during the product use phase, prior to products becoming waste and entering recycling processes, presents a major issue.

- Recyclate made from mixtures containing unknown PAC plastic should not be used for long-life products, due to the lack of evidence surrounding the long-term impact in secondary products. The existence of PAC plastic and the global nature of secondary materials markets does, therefore, present some risks of using recovered plastic in such applications. The uncertainty of whether recyclate may or may not contain PAC plastic, and the degree of oxidation likely to have occurred prior to recovery, therefore results in limits on the end-use for the recyclate.

  For shorter-life products, it may be possible to create a recyclate, which has no reduced properties over the short-term life of a particular product. However, most of the evidence suggests that the concentration of PAC plastic in the feedstock resin may be important – though evidence is not sufficient to suggest what limits should be followed. It must also not be ignored that any oxidation and degradation of PAC plastic that occurs prior to recycling will impair the recyclate

- Opinions and anecdotal evidence provided by the plastics recycling industry indicate there is significant risk associated with PAC plastic due to the way in which it is perceived by reprocessors. The inclusion of PAC plastic has a negative effect on the marketability of plastic films sent for recycling. The industry is keen to eliminate PAC plastic so as to minimise any effect on prices related to the quality and marketability of secondary materials.

5.2 Recommendations

The debate around the biodegradability of PAC plastic is not finalised, but should move forward from the assertion that PAC plastics merely fragment, towards confirming whether the timeframes observed for total biodegradation are acceptable from an environmental point of view and whether this is likely to take place in natural environments. It is still appropriate to refer to the material as PAC plastic (rather than oxo-biodegradable) as there is equally no evidence that *all* PAC plastic products will biodegrade. The variety of formulations—most of which are proprietary and confidential—and the lack of regulation means that there are no guarantees that all PAC

plastic will perform appropriately in the markets into which they are sold, and in environments they may end up.

The evidence is sufficient to suggest that bacteria can feed on PAC plastic if its molecular weight is sufficiently reduced. What is yet to be proven is that this happens in practice and that biodegradation happens in an acceptable timeframe. No suitable certifications are available currently, which allows any PAC plastic supplier to claim that this will happen in a certain environment to a particular set of requirements. Certifications from France and the UAE are not without shortcomings, and neither should be adopted as best practice by the EU. For PAC plastic to remain on the market, work to develop a (set of) European standard(s) should be a matter of priority.

One of the biggest issues to be confronted by both policy makers and the PAC plastics industry face when deciding on limits and controls is that there are no unified standards. We have observed throughout this research that the PAC plastics industry consists of different manufacturers and stakeholders, each of which claims to have developed the definitive method for assessing biodegradability; indeed, new methods appear to be surfacing all the time, with the latest coming from the UK's Queen Mary University on behalf of Symphony. Whilst the authors of this report agree that this new method is the most promising, it is in the early stages, and is being pushed by Symphony and the OPA. The French are keen to push their standard using the ATP test and the latest industry body to emerge—the OBPF—maintains that existing standards are suitable. This makes it less than straightforward to garner a rational body of evidence on the matter—as results from differing tests are incomparable—and to define a suitable approach through which one can be sure that the PAC plastics industry, as a whole, produces products that are not environmentally harmful.

In the meantime the PAC plastics industry should be prevented from selling their products into markets that have been conclusively proved to be unsuitable—primarily composting and AD markets. There is also no clear evidence to support the contention that PAC plastic is a solution to the problem of plastic in the marine environment: it is suggested that no form of communication that uses this as selling point, especially for single use items (the sort of products which PAC plastic is primarily aimed at) should be permitted.

It would go some way to alleviate fears of toxic effects if all PAC plastic products that were sold on the market were required to pass toxicity tests. As the PAC plastics manufacturers specifically state that their products are designed to help deal with the effects of littering it is incumbent upon them to demonstrate that each product they sell does not have a negative toxic effect on the environment that it is expected to be littered into. Such tests should be included as part of any European standard.

The issue of littering behaviour is something not confined to PAC plastic but applicable to all products that claim to be biodegradable or compostable—terms which are often

synonymous in the mind of the consumer. California recognised this issue and in 2011[237] regulated the use of these terms to help consumers make informed decisions without 'greenwash' and to target littering. Specifically:

> *"Environmental marketing claims, whether explicit or implied, must be substantiated by competent and reliable scientific evidence and meet specified standards to prevent misleading consumers about the environmental impact of degradable plastic products, including bags, food service ware, and packaging."*

This has resulted in court action on multiple occasions. The legislation also encourages manufacturers to work towards the production of appropriate standards that allow sound scientific tests to be performed to support any claim. Similar standardised regulation and alignment of nomenclature would also be beneficial to the EU and create a level playing field for manufacturers of products that are genuinely biodegradable in the relevant environments. It would also incentivise the PAC plastics industry towards aligning their efforts towards creating effective standards.

There are also issues surrounding the way in which disposal options for PAC plastics are communicated with consumers. It is clear that other biodegradable plastics (either bio-based or a mixture of bio and petroleum) are not compatible with current recycling. The message for consumers of this product is clear—they should be composted. The message for PAC plastic is less clear and the disposal options are potentially confusing for consumers. If consumers are told that PAC plastic is biodegradable it may be confused with other compostable plastics and put in the compost. Equally, if consumers are also told that PAC plastic is recyclable, they may also assume this of other biodegradable plastics. This is an ongoing issue that all plastic materials that claim to be biodegradable face and is linked to the way in which biodegradation is communicated as a whole.

[237] California Senate Bill No. 567 http://www.leginfo.ca.gov/pub/11-12/bill/sen/sb_0551-0600/sb_567_bill_20111008_chaptered.pdf

Appendices

A.1.0 Appendix 1: Market Study of the PAC Plastics Industry

This appendix provides further data to supplement the study on the impact of the use of Pro-oxidant Additive Containing (PAC) plastic on the environment. It provides an overview of the PAC plastics industry in Europe, and includes:

- a description of the PAC plastic supply chain;
- profiles of key actors in the supply chain;
- an estimated geographical distribution of global pro-oxidant additive sales;
- discussion on and estimated proportions of the different end uses of PAC plastic; and
- brief consideration of development potential in the market.

This appendix aims to put the production and use of PAC plastic carrier bags in the context of the broader PAC plastics market, both from a European and global perspective. This is anticipated to be of interest for any future plastics strategy the Commission might consider.

A.1.1 Methodology and Data Sources

In order to gain an overview of the PAC plastics market, several different methods of data collection have been used. First of all, a literature review was undertaken to establish the volume and type of market information that is publically available. This also identified the key actors in the supply chain, who were then contacted to collect primary quantitative and qualitative data for analysis. The quantitative data requested included: additive sales revenue and annual tonnage data; additive buyer names along with associated tonnage and revenue data; geographical breakdown of sales and buyers; and detail of PAC plastic products produced by buyers including product types, tonnages and sales revenues. Qualitative data requested included information on perceived market developments, drivers and barriers.

Data collection was focussed on the supply side of the market, due to the smaller number of actors in this section of the supply chain. The large number of actors on the demand side makes tracking final PAC plastic products more difficult.

It is worth noting that, as with any niche industry, the PAC plastics industry are wary of commercial data becoming available to their competitors. A further industry concern is market and political influence from both biodegradable and conventional plastics manufacturers. Obtaining comprehensive datasets has therefore been difficult, and only partial datasets have been obtained in the course of this study.

The data were aggregated into a model which allowed corroboration of similar data and also identified data gaps. Where it was not possible to fill these gaps with further

research and data collection, assumptions and extrapolations were made to allow estimations of the size of the market.

The key sources of information used in this market study are:

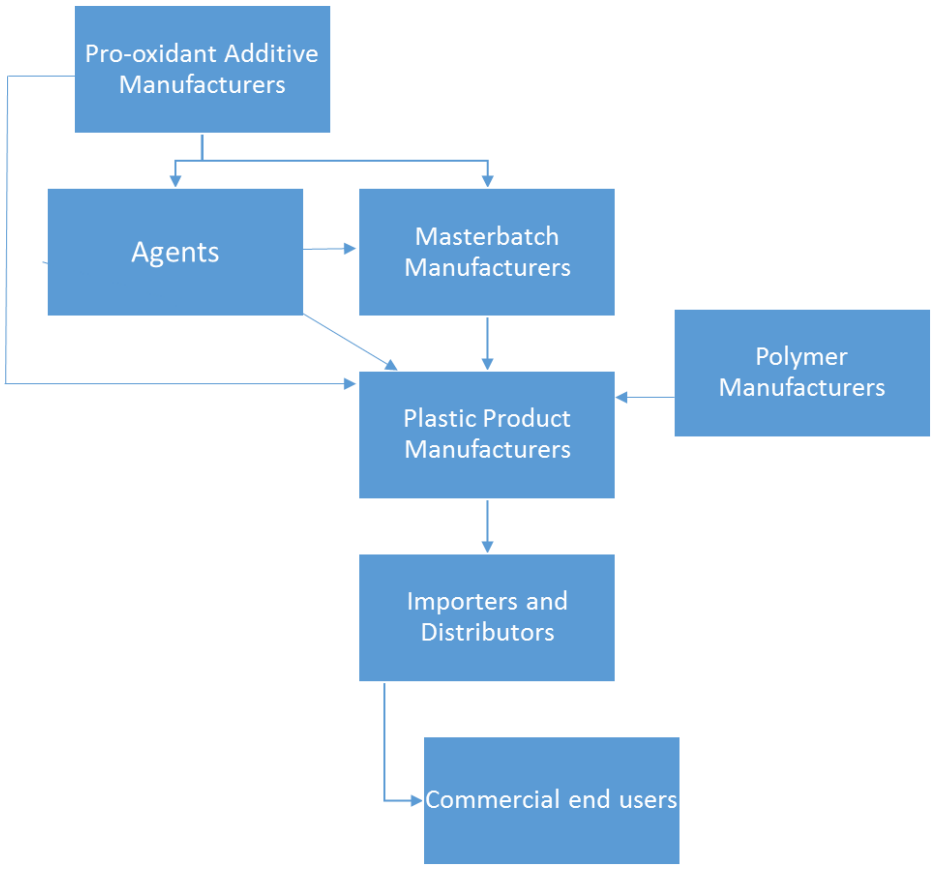
- academic literature on the PAC plastics industry;
- a non-exhaustive sample of company accounts from pro-oxidant additive manufacturers;
- data from the Oxo-Biodegradable Plastics Association (OPA); and
- data from other pro-oxidant additive manufacturers.

Any estimates or key data gaps are highlighted in the relevant sections. Unless otherwise referenced, all data presented have been provided in response to a questionnaire circulated as part of this market study. Data has been anonymised where requested.

A.1.2 Overview of the PAC Plastics Industry

The PAC plastic supply chain is shown in Figure A - 1 and is characterised by the roles as defined below (acknowledging that there is often some overlap between these roles within certain companies operating in this market). It may also be noted that the activities of certain businesses within this supply chain are not limited solely to that of PAC plastic.

Figure A - 1: PAC Plastic Supply Chain



Pro-oxidant Additive Manufacturers

The additive manufacturers all sell their product into global markets. There are nine companies known to manufacture pro-oxidant additives which are used for the manufacture of PAC plastic. Four of these are based in Europe, three in North America, one in Asia and one in the Middle East.

Agents and Masterbatch Manufacturers

Agents are companies which act as sales representatives directly for the additive manufacturers.

Masterbatch manufacturers are companies which buy pro-oxidant additives and create plastic 'masterbatches' to sell on to customers. Masterbatches are tailor-made mixtures of colour pigments and/or a wide range of additives designed to impart particular characteristics into a plastic product. As a widely used term not solely limited to pro-oxidant additives and their associated UV/heat stabilisers, masterbatches can include products containing flame retardants, antistatic agents, surface improvement agents, strengthening agents, electrical insulation improvement agents etc. Masterbatches are commonly produced and sold as pellets which are combined with plastic polymers in the plastic manufacturing process at the next stage.

Plastic Product Manufacturers

These companies combine either the pro-oxidant additives or masterbatches with polymers to produce plastic products. The plastic polymers are sourced from polymer manufacturers who appear to have no direct link to the pro-oxidant additive supply chain. The polymers appear only to be combined with additives by the plastic producers.

Importers and Distributors

The plastic product manufacturers may also import/export and/or distribute their products in a given country or region. This stage of the supply chain may also be distinct, with importers/distributors buying PAC plastic products from the manufacturers and selling them on to commercial end users.

Commercial End Users

These are companies which buy the PAC plastic products for use in their businesses or to sell on to consumers. For example these may be supermarkets for carrier bags, or farms (or farm supply stores) for agricultural mulch films.

Individual supply chains may have more or fewer stages than those outlined above, due to precise commercial arrangements between companies. However, the stages above incorporate the main functions provided by the actors identified in this study. Further detail on each of these stages is given in Sections A.1.2.1 - A.1.2.5 below.

A.1.2.1 Additive Manufacturers

There are currently two trade bodies which represent the PAC plastics industry on a global level – the Oxo-Biodegradable Plastics Association (OPA) and the Oxo-Biodegradable Plastics Federation (OBPF).

The OPA is a UK based organisation with 1,602 members throughout the world. A prominent member of the OPA is Symphony Environmental Technologies PLC (via one of its two subsidiary organisations: Symphony Environmental Limited (hereafter known as 'Symphony'), the other being Symphony Recycling Limited) which is also UK-based. Symphony is the only OPA member which manufactures a pro-oxidant additive. The other members are either manufacturers, importers and/or traders of pro-oxidant additive and/or PAC plastic products.

The majority of the other industry market leaders form the OBPF. Its membership includes:

- Add-X Biotech AB ('Add-X');
- EPI Environmental Products Inc ('EPI');
- Well Plastics Ltd ('Wells Plastics'); and
- Willow Ridge Plastics Inc ('Willow Ridge').

The remaining pro-oxidant additive manufacturers identified in this study, but unaffiliated with either PAC plastic trade association, are:

- EcoPoly Solutions Inc ('EcoPoly');
- GreenReady Plastic AS ('GreenReady Plastic');
- Programmable Life Inc ('Programmable Life'); and
- EnerPlastics LLC ('EnerPlastics').

A brief overview of these companies and the pro-oxidant additives they produce is provided below.

Symphony

Symphony manufactures a range of additives and masterbatches for plastic products, including its pro-oxidant additive **d2w**. There is only one d2w additive, with variations of the formula manufactured for particular buyer requirements. It is a UK-based company. Symphony sell through a network of 75 distributors operating across 100 countries.

Wells Plastics

Wells Plastics is the producer of the pro-oxidant additive **Reverte**, based in the UK. It also produces a range of other additives such as antimicrobials and flame retardants, and has been in the plastics industry for 32 years. Wells Plastics have a network of distributors around the world – including good coverage in the Americas, Asia, the Middle East and Australasia. In Europe it is partnered with Distrupol, a service and distribution supplier to the polymer industry in Europe. There are sales agents in the Netherlands, Lithuania, Spain, Italy and the Balkans but is notably absent in other European countries.

GreenReady Plastic

Nor-X Industries, formed in 2003, is now trading as GreenReady Plastic. It is the producer of the pro-oxidant additive **Renatura** and is based in Norway. It is understood that the use of Renatura was exclusively licensed to Diamant Art Corporation in 2007, through its subsidiary company, Bio-Plastics Film Inc. This was to produce plastic film products

under the tradename BioSmart.[238] GreenReady Plastics also make starch-based plastics and recycled plastic products. It sells its products through distributors in Europe, the United States, Canada and Asia.

Add-X

Add-X is a Swedish company which has been in the PAC plastics industry for 15 years. It produces the pro-oxidant additive **Addiflex**, with four grades of additive relevant to different end uses and process types. The grade with the greatest concentration of additive is used in the production of rubbish bags. A standard grade is used for carrier bags, agricultural films and some food packaging items. Add-X have distributors in over 50 countries across the world.

Willow Ridge

Willow Ridge is based in the USA and has produced a variety of plastic additives for 27 years. There are different grades of the pro-oxidant additive available: BDA, PDQ-H and PDQ-M, all of which are designed for use with different plastic polymers. It has a network of distributors across the globe. However, it does not currently list a distributor for Europe on its website.

Programmable Life

P-Life Japan Inc. was founded in 1994, under the name of Pacific Enterprise Japan Ltd., handling the products from Programmable Life Inc., USA. P-Life Japan Inc**.** was appointed regional representative of Programmable Life in 2003, giving it marketing and manufacturing rights for the **P-Life** pro-oxidant additive. There are two grades of P-Life additive: P-Life SMC2360 (powder form) and SMC2522 (liquid form). It sells its additive in over 20 countries in Europe, the Middle East, and the Americas with a stronghold in Asia, including Hong Kong, Philippines, Thailand and Malaysia. In Europe, P-Life is sold exclusively through Evive, a not-for-profit company established in 2009 to market the additive.

EPI

EPI is based in Canada. It produces the pro-oxidant additive **TDPA**. It has been in operation since 1991, and initially focussed on daily landfill cover, which it manufactures (more information on daily landfill cover is available in Section A.1.4.5). It now licences its additive to plastic manufacturers and works with them to develop PAC plastic products. It has warehouses in North America, Asia and Europe. It markets its additive directly and also through distributors in over 70 countries.

EcoPoly

EcoPoly is based in Canada and produces the pro-oxidant additive **OxoElite,** which is sold all over the world. It works with customers to tailor the additive to particular plastic

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[238] Ammala, A., Bateman, S., Dean, K., Petinakis, E., Sangwan, P., Wong, S., Yuan, Q., Yu, L., Patrick, C. and Leong, K.H. (2011) An overview of degradable and biodegradable polyolefins, *Progress in Polymer Science*, Vol.36, pp.1015–1049

products and end uses. Its customers focus on packaging films rather than carrier bags. Polymer Specialties International Ltd is a research and development company who own the intellectual property for OxoElite.

EnerPlastics

EnerPlastics is based in the United Arab Emirates (UAE) and produces the pro-oxidant additive **OBD.** It has been in operation since 1999 and also manufactures colour and other additive masterbatches. It is one of the largest masterbatch producers in the Middle East and sells into more than 58 countries across Europe, Africa, Middle East and parts of Asia.

A.1.2.2 Agents and Masterbatch Manufacturers

A proportion of the buyers of pro-oxidant additives are companies which act as intermediaries and market and sell the additive within a given particular geographical region. These companies will usually have exclusivity arrangements with a particular additive supplier. It is not uncommon for the additive manufacturers to have in excess of 50 agents across the globe, each working in particular countries.

Other companies at this stage of the supply chain use the additives to make plastic masterbatches to sell on. Often these companies sell a range of raw materials (such as polymers, plasticizers etc.), consumables (such as those used in packaging machines) and services (such as colour matching, technical support and lab testing) for the plastics industry as well. There are numerous companies, both within Europe and globally, that act in this capacity (as well as some of the pro-oxidant additive manufacturers outlined in Section A.1.2.1.).

A.1.2.3 Plastic Product Manufacturers

PAC plastic manufacturers may buy the pro-oxidant additives direct from the manufacturers, or through intermediaries or sales agents. They may buy just the additive itself or as part of a masterbatch. The plastic polymers may be sourced separately or with the additive/masterbatch.

Within this current study, 198 companies across the world were identified as buyers of pro-oxidant additives, 61 of whom are based in Europe. The proportion of these 198 buyers that are PAC plastic manufacturers is unknown. Full data on additive buyers was provided by two pro-oxidant additive manufacturers, with partial data from three other manufacturers. The actual number of PAC plastic manufacturers is therefore likely to be several times higher than these figures.

EcoPoly appears to be the only pro-oxidant additive manufacture which also manufactures and distributes PAC plastic products.

A.1.2.4 Importers and Distributors

Depending on the precise logistics of individual supply chains, the pro-oxidant additive itself may be imported into the country of production and sale, or the plastic product may be imported into the country of sale after manufacture elsewhere. PAC plastic importers usually also act as distributors within a country or region. There are hundreds of distributors around the globe for PAC plastic.

A.1.2.5 Commercial End Users

Pro-oxidant additives are used in several different types of plastic polymers, including polyethylene (PE), polypropylene (PP) and polyethylene terephthalate (PET). A wide range of PAC products can be made, all with different end users. End users include:

- supermarkets and bakeries (i.e. plastic carrier bags, such as Carrefour who have used Symphony's d2w additive[239]);
- goods retailers such as clothing and electrical items (i.e. plastic carrier bags);
- food and drink suppliers (i.e. for various packaging applications);
- farmers and growers (i.e. agricultural mulch films);
- newspaper and magazine publishers (i.e. for use in film wrapping);
- financial institutions (i.e. plastic security bags used to deposit money such as HSBC (who use P-life));
- hospitals (i.e. disposable aprons and gloves); and
- airlines (such as Pakistan International Airlines whose packaging is made with Symphony's d2w additive[240])).

This is not an exhaustive list but provides an overview of some of the markets within which PAC plastic is used.

A.1.3 PAC Plastics Industry Market Shares

There are a vast number of different companies operating as distributors, importers and commercial end users within the PAC plastic supply chain. Some of these companies also fulfil more than one vertical function within the supply chain. Therefore it is not possible to estimate the market shares of each individual company. (Market shares of end uses of PAC plastic are discussed in Section A.1.5.)

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[239] Beaufort (2015) *Symphony Environmental Technologies Plc*, accessed 16 March 2017, https://www.beaufortsecurities.com/videos/Symphony-Environmental-Technol_S.pdf

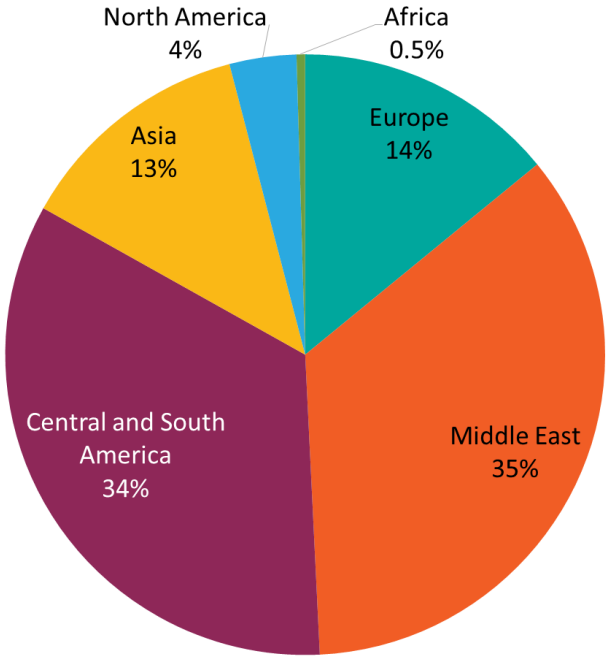
[240] Symphony Environmental Technologies Plc (2016) *Pakistan International Airlines - 3 Year Agreement*, accessed 16 March 2017, http://www.symphonyenvironmental.com/pakistan-international-airways-3-year-agreement/

Our understanding is that the manufacturers identified in Section A.1.2.1 constitute the majority of global (and certainly, European) pro-oxidant additive manufacturers. Although data were requested from these manufacturers, due to commercial sensitivities, insufficient data were supplied to establish the market shares of each pro-oxidant additive manufacturer. The data supplied by a European and a non-European manufacturer reveals that from just these two manufacturers at least 1600 tonnes of pro-oxidant additive was placed on the market globally in 2016, at least 200 tonnes of which was in Europe. With nine known additive manufacturers the actual tonnage is certain to be higher than this. Further quantification to estimate the amounts of PAC plastic placed onto the market are provided in Section A.1.5.

A.1.3.1 Global Geographical Sales

Sales of pro-oxidant additives are influenced by policies which stipulate or encourage the use of PAC plastic over other plastic types. Countries such as Pakistan, UAE and Yemen have legislated in favour of PAC plastic (further information on this is available in Section 4.4.1. Therefore, even European-based additive manufacturers have strong demand from outside of Europe. Figure A - 2 shows the estimated share of global sales of pro-oxidant additive in 2016 broken down by geographical region. This estimation is based on aggregated tonnage data from a European and a non-European manufacturer. It has not been possible to estimate detailed data on a European country-by-country basis. It must also be stressed that this data should only be considered as indicative, since manufacturers for which data were not available may have a different geographical spread to those for which data were provided.

Figure A - 2: Estimated Share of Global Sales of Pro-Oxidant Additive in 2016, by Region



Note: Data does not sum to 100% due to rounding.

From the data available, the Middle East and Central and South America were the two largest markets for pro-oxidant additives, with over a third of the market each. Asia represents approximately an eighth of the total, with European sales just 14% of global sales. Both North America and Africa have a small proportion of sales.

In terms of how this market has changed over recent years, there is some limited data on the geographical spread of sales for Symphony (a UK based company), which is also available historically from its financial accounts. This is shown in Table A - 1.

Table A - 1: Percentage Share of Global Pro-Oxidant Additive Sales, Symphony, 2010-2015, by Region

Year	Europe	North, South and Central America	Rest of World
2010	19%	51%	29%
2011	23%	54%	23%
2012	28%	43%	29%
2013	21%	47%	32%
2014	22%	48%	30%
2015	15%	50%	35%

Source: Calculations are based on sales data sourced from Companies House, Symphony Environmental Limited Financial Accounts. Although these figures relate to company turnover, it is understood that sales of d2w account for the majority of this turnover.[241]

Symphony's greatest proportion of sales are in North, South and Central America, with approximately half of all additive sales coming from this geographical region. The data also show a trend of a declining share of sales from Europe since 2012, which is reflected in the increase in the overall share of sales attributed to the rest of the world since then. This is likely to be driven by increasing sales in the Middle East due to legislative policies introduced in many Middle Eastern countries.

A.1.4 Overview of End Uses of PAC Plastic

PAC plastic can take a wide range of forms, as pro-oxidant additives are designed to be incorporated into a variety of different plastic polymers. Common polymers used in PAC plastic are PE, PP and PET. The pro-oxidant additive manufacturers claim their additives

[241] Companies House *Symphony Environmental Limited - Overview*, accessed 16 March 2017, https://beta.companieshouse.gov.uk/company/02967867

are used in as many as 150 products, which have been grouped into the following main end use types:

- agricultural applications;
- rubbish bags;
- carrier bags;
- food packaging;
- landfill cover; and
- other miscellaneous applications.

These end uses are described in more detail below.

A.1.4.1 Agricultural Applications

PAC plastics have been used for many years in agricultural activities. They are used in a variety of applications, such as for wrapping hay, potting containers, tree ties and vegetable sacks. However their main use in the industry is in mulch films. Mulch films are widely used as a protective covering in commercial agriculture to help provide improved conditions for crop growth by reducing weeds, maintaining moisture and protecting from extremes of temperature. They were created as an alternative to conventional PE mulch films which are difficult to recover, almost impossible to recycle due to contamination and cannot (legally in certain countries) be incorporated into the soil.[242] PAC plastic mulch films are often (where legal) left in fields and are then ploughed back into the soil.

The main utilisation of pro-oxidant additives in agricultural mulch films was undertaken by a company called Ciba Speciality Chemicals using EPI's TDPA additive. These films were sold under the tradename of Envirocare.[243] In 2008 Ciba was obtained by the German chemical company BASF, and sales of Envirocare ended in 2010.[244] Now available on the market is DegriFilm, made by the additive manufacturer EcoPoly. It tailors the additive and product to each agricultural application and sells directly into the market. Other notable manufacturers/distributors of PAC plastic mulch film include Solplast who make Acosol, a brand of mulch film which can (as required) be made with oxo-degradable properties. Solplast is part of the Armando Álvarez Business Group, the largest Spanish manufacturer of PE plastic films. Eco-one is another agricultural mulch

[242] Briassoulis, D., Miltiadis Hiskakis, Epifaneia Babou, and Ioanna Kyrikou (2014) Analysis of Long-term Degradation Behaviour of Polyethylene Mulching Films with Pro-oxidants under Real Cultivation and Soil Burial Conditions, *Environmental Science and Pollution Research*, Vol.22, No.4, pp.2584–2598

[243] Ammala, A., Bateman, S., Dean, K., Petinakis, E., Sangwan, P., Wong, S., Yuan, Q., Yu, L., Patrick, C. and Leong, K.H. (2011) An overview of degradable and biodegradable polyolefins, *Progress in Polymer Science*, Vol.36, pp.1015–1049

[244] PNChina.com (2010) *BASF drops Envirocare to focus on Ecovio*, accessed 16 March 2017, http://www.pnchina.com/en/Detail.aspx?id=1287089048&cat=120

film brand, although it is unclear who manufactures Eco-one and which pro-oxidant additive is used. Eco-one can be sourced from several online retailers.[245]

A.1.4.2 Rubbish Bags

One of the main uses of PAC plastic is the manufacture of bags designed to hold household, garden or commercial rubbish. This includes bags designed to line bins and also small bags designed to hold animal waste.

Many of the companies which manufacture and distribute PAC plastic rubbish bags also produce a range of other PAC plastic products. Some of the main PAC plastic rubbish bag retailers are:

- Discount Degradable Bags, part of the Degradable Bag Division of Polybags Limited, UK. It distributes rubbish and carrier bags using EPI's TDPA additive;
- Richmond plastics, based in Canada, also supplies the UK with rubbish and carrier bags made with EPI's TDPA additive;
- Reddipak, one the UK's largest suppliers of packaging products, which it manufactures in the UK and Asia. It manufactures rubbish, carrier bags and a range of other products with EPI's TDPA additive; and
- Evive Europe Ltd which makes carrier bags and rubbish bags with the P-Life additive.

These products are sold to both commercial and non-commercial customers.

A.1.4.3 Carrier Bags

PAC plastic can also be used in the production of all types of single-use carrier bags. This includes:

- very lightweight plastic carrier bags with a wall thickness below 15 microns. Very lightweight bags are often provided in supermarkets and bakeries to hold loose food items such as fruit and vegetables;
- lightweight plastic carrier bags which have a wall thickness between 15 and 50 microns. These are of the type found at supermarket checkouts and some clothing and goods stores for carrying purchases; and
- thicker plastic bags which are given out to carry products often from more expensive clothing and goods stores.

Some of the main producers and distributors of PAC plastic carrier bags are detailed in A.1.4.2.

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[245] Heartnut Grove Inc *Eco-One Oxo-Biodegradable Plastic Mulch*, accessed 16 March 2017, http://heartnutgrove.com/horticulture/eco-one-oxo-biodegradable-plastic-mulch/

In the UK, the supermarkets Tesco and the Co-operative switched to lightweight PAC plastic carrier bags made using Symphony's d2w additive in 2006 and 2002 respectively. However, the Co-operative stopped using them in 2010 in response to DEFRA's research on the subject[246] [247], and Tesco stopped in 2011 reportedly because the bags were weaker than conventional ones.[248] It is believed that Carrefour continues to be an end user of carrier bags made with Programmable Life's P-Life additive. It is understood that the majority of other buyers of PAC plastic carrier bags are small and medium sized buyers from across the retail industry.

A.1.4.4 Food Packaging

PAC plastic is used for a variety of food packaging applications. These include bread bags, food trays and films, freezer bags and drinks bottles. It is worth noting that if PAC plastic is to be used for food packaging then it must be compliant with any relevant food safety requirements in the country of sale. This is true for all types of plastic.

The main manufacturer identified in this study is CPS Flexible Ltd, based in the UK, who manufactures Oxolife packaging films using the d2w additive for both PE and PP plastics.

A.1.4.5 Landfill Cover

A niche application for PAC plastic which was developed many years ago is landfill cover. In many countries, it is mandatory for a cover to be applied to the active face of a landfill at the end of each day's operations, in order to reduce odour and the potential for waste to escape. Soil or aggregate can be used for this purpose, but PAC plastic sheeting reduces the amount of vertical space required. The sheeting is marketed as degrading over time in order to allow the movement of gases and liquids within the landfill.

The only brand of PAC plastic landfill cover identified is Enviro Cover, made using EPI's TDPA additive. EPI market the brand, but it is unclear whether EPI actually manufactures the product itself. In the USA there are landfill operating requirements, such as statutory odour control requirements, which products must be compliant with before their use is approved. It is understood from EPI's marketing material that Enviro Cover has been approved in thirteen states and also in countries such as Canada, Argentina, Australia, Finland, and the UK.[249] EPI have agents in Poland, Portugal, the UK, Italy, France and Asia

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[246] The Telegraph (2010) *'Biodegradable' plastic bags may not be as eco-friendly as thought*, accessed 16 March 2017, http://www.telegraph.co.uk/news/earth/earthnews/7422006/Biodegradable-plastic-bags-may-not-be-as-eco-friendly-as-thought.html

[247] DEFRA (2015) *Review of Standards for Biodegradable Plastic Carrier Bags*, December 2015

[248] Packaging News (2011) *Tesco drops oxo biodegradable bags*, accessed 16 March 2017, http://www.packagingnews.co.uk/news/tesco-drops-oxo-biodegradable-bags-17-08-2011

[249] EPI Environmental Products Inc. (2014) *Enviro ™ Cover Controls Odours in Landfills*, August 2014, http://www.envirocoversystem.com/pdf/paper_enviro_cover_controls_odours_in_landfills.pdf

for Enviro Cover. It is likely that Enviro Cover represents a large majority, if not all, of the market for PAC plastic landfill cover.

A.1.4.6 Other Miscellaneous Applications

There are a large range of other applications for PAC plastic which don't fall into the uses outlined in Section A.1.4.1-A.1.4.5. Notable other uses include disposable medical supplies such as gloves and aprons, multi-purpose packaging materials such as films and bubble wrap, envelope windows and plastic covers for mail items and courier/security bags.

A.1.5 Market Shares of End Uses of PAC Plastic

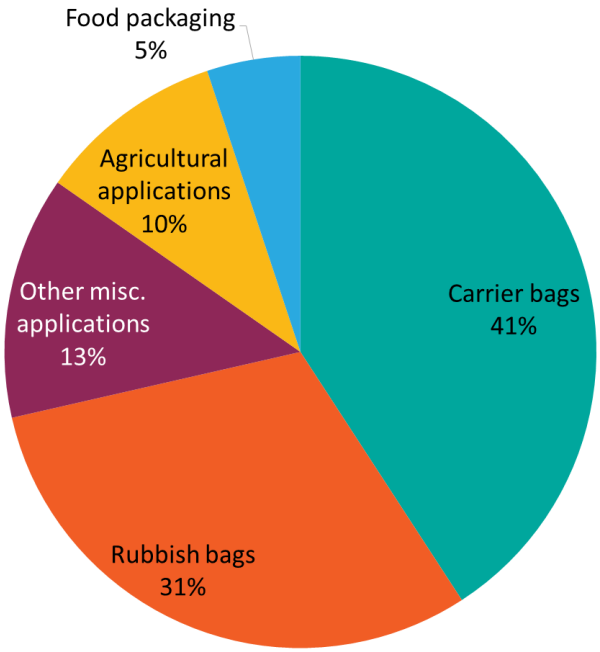
In order to quantify and compare the amount of PAC plastic being used in different products and end uses, data were sought from both the supply and demand side of the industry. No data were received from the demand side of the industry. One of the pro-oxidant additive manufacturers claimed it did not know what its buyers made with the additives sold to them, and others felt unable to supply this data due to confidentiality issues. However, the data supplied by a European and a non-European pro-oxidant additive manufacture, reveals that from just these two manufacturers at least 155,000 tonnes of PAC plastic was placed on the market globally in 2016, and that 20,000 tonnes of this was within Europe.

With nine known additive manufacturers, the actual quantities are certain to be higher than this. No quantitative data is available to accurately quantify production from the other manufacturers, nor the geographical territories within which their products are sold. Taking a crude assessment, factoring up (on the ratio 9:2) to seek to account for manufacturers for which no data is available, there could be 700,000 tonnes of PAC plastic placed annually onto the global market or 100,000 tonnes placed onto the European market (acknowledging the margin of error on these figures is very large).

Figure A - 3 shows market shares of the different end uses of PAC plastic, based on the data provided by one of the non-European pro-oxidant additive manufacturers. These data should therefore only be considered as indicative; were data to be available from a larger number of additive manufacturers, this could change the market shares from this representation.

Figure A - 3 shows the majority of PAC plastic from this additive manufacturer is used in the production of single-use carrier bags, closely followed by a third used to make rubbish bags. Together, these applications account for 72% of output. Food and other packaging applications account for almost a fifth of the output, with agricultural applications representing a small share. Landfill cover applications are not represented in this data, and as explained in Section A.1.4.5, this is likely to be because the landfill cover market is dominated by one additive manufacturer. The market share for landfill cover is therefore unknown.

Figure A - 3: Market Share of End Uses of PAC Plastic from one Additive Manufacturer



Note: Data obtained from one of the nine additive manufacturers identified as part of this study.

It seems likely from marketing material that the majority of pro-oxidant additives are considered suitable for a variety of different application types. A possible exception to this is landfill cover which appears to be dominated by TDPA, though it is not clear whether this is because the additive has been specifically formulated for this particular application, or just that this is a market of particular focus to this manufacturer. Similarly, EcoPoly also appears to be much more active in the packaging films sector, and less so in relation to carrier bags.

A.1.6 Market Development Potential

As part of the questionnaire circulated for this market study, the pro-oxidant additive manufacturers were asked about their perspectives on the potential developments within the industry. Several key points were raised.

With an increase in public awareness and concern regarding litter (particularly marine plastic litter and its effects both on marine ecosystems and the human food chain) the pro-oxidant additive industry is seeking to cultivate demand from end users of plastic in numerous markets for products beyond just carrier bags.

The industry also cites legislation which advocates the use of PAC and/or biodegradable plastic as a key driver for future demand, along with effective enforcement of such legislation. For certain applications there is strong competition from a number of products including biodegradable plastics (where raw material can either be starch based, cellulose based, chemically synthesised, bacteria based, or fossil based), enzyme-

mediated degradable plastics (conventional plastics with organic additives), as well as conventional plastic. As such, environmental and related legal judgements on the appropriateness of PAC plastic or their alternatives are of great importance.

The final aspect of relevance is legislation which seeks to reduce plastic use generally. A clear example is carrier bags legislation in Europe which is substantially shrinking this particular market application.

In order to quantify the market development potential for PAC plastic, a comparison of the size of the total plastic and PAC plastic markets in Europe is provided in Table A - 2.

Table A - 2: Estimate of Total Plastic and PAC Plastic Placed on the European Market, Tonnes per Annum, 2016

Plastic End Use	Total Plastic (Annual Tonnes)	PAC Plastic (Annual Tonnes)
Agricultural applications	80,000[250]	10,000
Rubbish bags	500,000[251]	30,000
Carrier bags	1,500,000[252]	40,000
Food packaging	20,000,000[253]	5,000
Landfill cover	unknown	unknown
Other misc. applications	unknown	15,000

Note: PAC plastic tonnes are based on an estimate of 100,000 tonnes of PAC plastic on the European market, as detailed in Section A.1.5. All figures are estimates based on available data.

[250] European Bioplastics (2016) *The upcoming revision of the EU Fertilisers Regulation and the benefits of biodegradable plastic mulch films.*, accessed 21 March 2017, http://www.european-bioplastics.org/the-upcoming-revision-of-the-eu-fertilisers-regulation-and-the-benefits-of-biodegradable-plastic-mulch-films/

[251] Estimate based on 219,000,000 households in the EU using 52 rubbish bags a year at 30g of weight, and increased by 50% to account for commercial use.

[252] Estimate based on 99 billion plastic bags placed on the EU market in 2010 at an average weight of 15g per bag, European Parliamentary Research Service (2014) *Reducing the use of lightweight plastic carrier bags*, 2014, http://www.europarl.europa.eu/RegData/bibliotheque/briefing/2014/140800/LDM_BRI(2014)140800_REV1_EN.pdf

[253] Estimated based on demand for general packaging in Europe, *PlasticsEurope - Plastics - the Facts 2016*, accessed 21 March 2017, http://www.plasticseurope.org/Document/plastics---the-facts-2016-15787.aspx?Page=DOCUMENT&FolID=2

A.1.6.1 Agricultural Applications

PAC plastic has to compete with both conventional plastic mulch films and biodegradable mulch films (such as those composed of corn-starch) in this market. The marketing of PAC plastic mulch films focuses mainly on potential savings arising from the labour and time needed to collect and dispose of conventional plastic films from the fields. PAC plastic mulch films may therefore be considered as sitting in the market between conventional plastics and biodegradable films, with high competition existing between these products. Further market development can therefore be expected to be dependent upon cost balances between competing film types, as well as on performance characteristics between them, and on any further shift to the use of mulch films within farming business practices. It should however be noted in relation to mulch films that the ploughing-in of PAC plastic has been prohibited in the UK, so such policies are very relevant to this sector (see Section 4.4.3).

A.1.6.2 Rubbish Bags

PAC plastic rubbish bags, intended to contain household and commercial mixed general waste, have been observed as marketed as degrading in landfill at a greater speed than non-PAC plastic bags. The suggestion is offered that they are, therefore, a more environmentally-friendly option for consumers to choose. Findings demonstrated in Section 4.1.4, however, conclude that degradation of PAC plastic is prevented under anaerobic conditions in landfill. It may be the intention that these bags should break apart within the initial aerobic stage in the higher levels of the landfill. Even so, the environmental performance claim appears subjective, unsubstantiated and even inconsistent with performance characteristics claimed by some within the PAC plastics industry. Notwithstanding these issues, with future increases in recycling and limits on waste to landfill expected through the European Commission's Circular Economy Package, this market may experience some shrinkage in future, and a bag which claims to perform well in landfill may become less relevant.

A.1.6.3 Carrier Bags

Historically the PAC plastics industry had some success with increasing their share in the lightweight plastic carrier bag market, with several major supermarkets switching their single-use bags to PAC plastic in the 2000s. However, many of these supermarkets switched back to using conventional plastic due to a range of factors, thought to include confusion on whether "oxo-degradable" meant compostable, concerns on the recyclability of the bags, and continuing concerns relating to litter. With shifts in public awareness regarding single-use plastic bags and an increase policies prohibiting or levying charges on them, many supermarkets have shifted focus towards multi-use carrier bags. The data presented above suggests that the current PAC plastic share of the carrier bag market is small, and hence there may be space for the industry to seek to make further headway. There remains a knowledge gap, however, as to whether biodegradability claims associated with PAC plastic carrier bags might worsen littering

(as is noted in the main report). Thus the only conclusion that can be proffered with certainty is that overall volumes of single-use plastic bags in Europe are declining generally due to the recent, and yet to be fully realised, plastic bags legislation.

A.1.6.4 Food Packaging

PAC plastic used for food packaging is indicated in Table A - 2 to have the smallest percentage market share of any of the identified product types. It may be that uptake has so far been limited due to concerns over the recyclability of PAC plastic (as is highlighted in the main report) or simply a perceived risk of the onset of degradation before the packaging has served its useful life. Though no further prognosis can be given here, it is notable that the UAE originally intended to introduce legislation to compel the use of PAC plastic in all disposable plastic products, but this did not occur and the legislation applies to carrier bags only. This does, however, remain an important sector as the annual tonnage of food packaging dwarfs all other sectors shown here.

A.1.6.5 Landfill Cover

The potential market for daily landfill cover is likely to vary geographically according to the amount of formal landfill infrastructure available in different countries, and regulatory requirements on landfilling operations. Many Western European countries are experiencing a decline in the number of active landfill sites, whereas those countries in the process of formalising their waste infrastructure may drive an increase in demand for this kind of product. However, as explained above, the tonnages of PAC plastic landfill cover, as well as the total tonnages of plastic landfill cover, placed annually on the European market is unknown and therefore the development potential cannot be quantified.

A.1.6.6 Other Miscellaneous Applications

With pro-oxidant additives used in several plastic polymers (including PE, PP and PET), in theory any disposable plastic product could be made with PAC plastic. Most of these are likely to be relatively minor applications, such as the example above of disposable medical gloves, but there could remain potential for the PAC plastic market to expand into new products should this be seen by the various product manufactures as beneficial.

A.2.0 Appendix 2: Supplementary Data

Table A - 3: Time for Plastics to Reach Maximal Absorption of Hydrophobic Organic Compounds on Incubation at Environmentally Relevant Concentrations

Compound	Plastic type	Plastic size	Incubation medium (concentration of compound –environmentally relevant?)	Incubation time – Equilibrium reached?	Reference
Phe (a PAH) **DDT**	PVC PE	Microplastics - 200-250µm	0.6-6.1 µg/l Phe 0.8-3.1 µg/l DDT Yes	360h - equilibrium after 24hrs.	Bakir 2014 (estuarine simulation)
Phe **DDT** **PFOA** **DEHP**	PVC PE	Microplastics - 200-250 µm	As above - Yes	360h - equilibrium after 24hrs. EXCEPT DDT onto PE = 48h	Bakir 2014 (gut simulation)
Phe	PE PVC PP	Microplastics - 200-250 µm	Yes	120h - equilibrium after 24hrs.	Teuten 2007

Compound	Plastic type	Plastic size	Incubation medium (concentration of compound –environmentally relevant?)	Incubation time – Equilibrium reached?	Reference
PAH	PE PP	Pellets		Naphthalene between 21 (PP) - 28 (PE) days for 90% equilibria. Pyrene - 49 days (PP)128 days (PE). Phe 63 days (PP), 105 days (PE).	Karapanagioti (2010) [cited in Bakir 2014 (gut)]
PAH, Fluorene, Phenanthrene Anthracene Fluoranthene	LDPE, HDPE	Pellets	1-100 µg/l PAH i.e. 0.001-0.1µg/l Yes	1 week - did not reach equilibrium for all compounds but 90% reached in 24hrs Sorption may be faster for lower density plastics.	Fries and Zarfl (2012)

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