



Department  
for Environment,  
Food & Rural Affairs

# Updated review of the science relating to pro-oxidant additive containing plastic or oxo-degradable plastics

Hazardous Substances Advisory Committee

October 2025

Version: 1

We are responsible for improving and protecting the environment. We aim to grow a green economy and sustain thriving rural communities. We also support our world-leading food, farming and fishing industries.

Defra is a ministerial department, supported by 34 agencies and public bodies.



© Crown copyright 2025

This information is licensed under the Open Government Licence v3.0. To view this licence, visit [www.nationalarchives.gov.uk/doc/open-government-licence/](http://www.nationalarchives.gov.uk/doc/open-government-licence/)

Where we have identified any third party copyright information you will need to obtain permission from the copyright holders concerned.

This publication is available at [www.gov.uk/defra](http://www.gov.uk/defra)

Any enquiries regarding this publication should be sent to us at [Plastics.Consultation@defra.gov.uk](mailto:Plastics.Consultation@defra.gov.uk).

## Contents

Scope.....	4
Approach .....	4
Key findings .....	6
1. The Chemistry of PAC plastics.....	6
2. The environmental degradation of PAC plastics .....	9
3. The environmental and human toxicity of PAC plastics and their degradation products .....	14
4. Policy considerations and remaining knowledge gaps .....	16
5. Conclusions regarding the current state of knowledge regarding PAC plastics .....	17
Glossary of terms.....	18
References .....	19

## Scope

The 2019 [review of oxo-degradable plastics](#) by the HSAC concluded that: “The literature as a whole suggests that current oxo-degradable plastics have not been demonstrated to provide a substantial improvement in terms of complete biodegradation or breakdown over existing standard plastics in the open environment”.

The Hazardous Substances Advisory Committee (HSAC) were invited in early 2024 to undertake a review of the literature published since 2019, to assess whether sufficient evidence exists of the breakdown or biotransformation of Pro-oxidant Additive Containing plastic (PAC plastic) otherwise known as oxo-degradable or oxo-biodegradable plastic under natural conditions.

The specific scope of this review, which is restricted to literature published between 2019 and 2024, is as follows:

- Has the science regarding the degradation or biotransformation of pro-oxidant additive containing plastic (PAC-plastic, otherwise known as oxo-degradable or oxo-biodegradable plastic) moved on since 2019?
- Has PAC plastic formulation moved on since 2019, and what evidence is available showing the impacts of these new formulations?
- Given any changes in the above, are manufacturers’ claims on the degradability of their products plausible?

The review is structured into the following sections which provide brief summaries of:

- The chemistry of PAC plastics and their (bio)degradation processes and current formulations;
- (1) The current knowledge on the fate of PAC plastics, especially under realistic environmental conditions, including from mesocosm studies, studies in soil and other environments; and
  - (2) The toxicity of PAC plastics to organisms at a variety of trophic levels and in a range of natural environments, as well as to humans, including from microplastics generated as a result of the partial degradation of PAC plastics.

Based on these summaries of the current state of the science, we will draw conclusions regarding the evidence for degradability of PAC polymers under natural conditions.

## Approach

The [original review of the literature](#) on PAC plastics by HSAC sought to obtain an overview of the topic that reflected current knowledge, rather than exhaustively reviewing the literature. This updated review takes a similar approach and is focussed on understanding progress in the science and evidence related to PAC degradation in the environment and

the potential for toxicity, based on research findings published since the previous HSAC review in 2019.

Using Web of Knowledge, an initial search was performed using the search terms “PAC OR pro-oxidant additive containing Plastics AND Degradation OR Fate OR Toxicity” and “oxo-degradable plastics AND Degradation OR Fate OR Toxicity”, which returned 170 publications – these were initially classified into (1) chemistry, (2) fate and degradation, (3) toxicity assessment, and (4) policy or perspectives, and then further classified as reviews or original data-containing publications. The original data publications were assessed in detail and are summarised in the tables presented as appendices to this document. Reviews were evaluated by examining the original articles for key statements regarding the degradability of PACs under environmental conditions, key recommendations and concerns, and to identify trends or patterns.

The literature analysis by the core team was supplemented by a call for evidence that was open to the public from 26<sup>th</sup> January to 29<sup>th</sup> February 2024, and which received 11 submissions consisting of publications, project reports and other grey literature much of which was already in the public domain, but some of which was confidential information shared for the purpose of the review. A non-exhaustive search of patent literature was also performed to assess evolution of PAC plastic formulations.

# Key findings

## 1. The Chemistry of PAC plastics

### Defining PAC plastics for the purpose of this review

Pro-oxidant additive containing (PAC) plastics is a term that describes a growing number of plastics which are designed to degrade in the unmanaged natural environment (open-air, soil, aquatic systems) through oxidation and other processes under the action of UV light and heat. Directive (EU) [2019/904](#) of the European Parliament and of the Council on the reduction of the impact of certain plastic products on the environment states that oxo-degradable plastic means “plastic materials that include additives which, through oxidation, lead to the fragmentation of the plastic material into microfragments or to chemical decomposition.” PACs are generally polyolefins, i.e., polymers of alkene hydrocarbons such as polypropylene (PP), polyethylene (PE), polystyrene (PS), high, low and linear-low density polyethylene (HDPE, LDPE and LLDPE), and vinyl polymers such as polyvinyl chloride (PVC). They account for 75% of the global plastic production and are the largest class of commodity thermoplastic polymers (Sciscione et al., 2023). Note that PAC plastics are primarily used in single-use applications, meaning that they are broadly incompatible with the development of a circular economy broadly (Dintcheva NT, 2024).

The degradation process of polyolefins can be accelerated by the addition of pro-oxidants (also referred to as pro-degradants). PAC plastics may have up to 5% loading by weight of a pro-oxidant chemical to enhance their UV-degradation and fragmentation into smaller pieces thus increasing their bioavailability to microbes for mineralisation to CO<sub>2</sub>, although the evidence for microbial assimilation is limited ([Sciscione](#) et al., 2023; Reddy et al., 2009). The most used pro-oxidants are transition metals (e.g., Fe, Co, Mn, Cu, Ce or Ni) in the form of salts (e.g., carboxylates, dithiodicarbamates, acetylacetonates) or organic complexes, although more recent publications have also utilised naturally occurring photoinitiators such as benzophenone, benzoin or TiO<sub>2</sub> nanomaterials, and even extracted chlorophyll.

PAC plastics are also referred to as ‘oxo-degradable’ plastics, ‘oxo-biodegradable’ plastics and those containing ‘biotransformation’ additives (Sciscione et al., 2023). The distinction between oxo-degradable and oxo-biodegradable is presumably intended to differentiate between the abiotic (e.g., UV degradation and the radical chain mechanism) and biotic (i.e., microbial assimilation of the small fragments and their subsequent mineralisation) stages of the degradation processes. However, these terms are often used interchangeably. Given that the dominant degradation steps arising from the pro-oxidant additives are abiotic (see below), the term ‘oxo-biodegradable’ may be confusing.

PAC plastics are thus distinct from biodegradable polymers which are meant to break down purely biotically, as PACs are conventional polymers with additives designed to enhance the rate at which they fragment. It is unclear whether PACs break down at the molecular or polymer level. There are significant concerns that the resulting microplastics

are left in the environment indefinitely until they eventually break down into nanoscale entities: an extensive evidence review concludes that “microplastics form during the biodegradation of all plastics in the open environment; PAC plastics are no exception” ([Sciscione et al., 2023](#)).

## **PAC plastics degradation, pro-oxidant additives and recent developments**

Degradation of PAC plastics occurs via fragmentation caused by free radicals that react with oxygen in the atmosphere, typically driven by interaction with UV light and heat. There are several different ways to initiate the first radical species and the subsequent oxygen addition reactions, some of which are activated during the plastic production (Mamin et al., 2023), including:

- (1) Direct oxidation of C–H by molecular or atomic oxygen, which has quite a high activation energy.
- (2) Thermal rupture of C–C or C–H bonds, which also has quite a high activation energy
- (3) Mechanochemical rupture of C–H bond, which could take place at the extrusion stage during the manufacturing of polymer or composite (Scott, 1995). Once radicals are generated, another oxidation reaction takes place.
- (4) Oxidation by molecular oxygen (O<sub>2</sub>);
- (5) Reaction of O<sub>2</sub> with unsaturated carbon–carbon bonds (impurities).

Thus, a pre-activation step is often required through UV or heat to start the degradation process. This is one of the major challenges noted with PAC plastics, that the required UV intensity and temperature may not be achieved under environmental conditions typical of the northern latitudes for example (Devalla, 2022). A wide range of pro-oxidant additives have been explored to initiate the reactions noted above, as summarised in Table 1.

**Table 1: Types of pro-oxidant additives that have been investigated to enhance the degradation of plastics, including commercial variants where these could be identified. Note that several categories can be utilised in parallel (adapted and extended from Ammala et al 2011).**

<b>Prodegradant type</b>	<b>Role</b>	<b>Example additives</b>	<b>Commercial names</b>	<b>References</b>
Natural fillers	Enhance adhesion between polymer matrix and filler particles	Vegetable fillers (sunflower husk, flax shive, mixed herb hay), pectin, chitosan, cellulose diacetate and starch, microcrystalline cellulose	D <sub>2</sub> W AddiFlex Reverte	Ammala et al., 2011; Mamin et al., 2023
Metal salts as stearates, carboxylates	Catalysts, react with O <sub>2</sub> to promote bond breakage	Mn, Co, Fe, Ni, and Zn acetylacetonates	D <sub>2</sub> W TDPA, Renatura	Ammala et al., 2011

<b>Prodegradant type</b>	<b>Role</b>	<b>Example additives</b>	<b>Commercial names</b>	<b>References</b>
Combinations of metal activators and deactivators	Activators used to tune the reaction conditions, deactivators used to prevent/ modulate degradation until specific conditions are met	Blend of metal pro-oxidants (iron stearate) and antioxidants/UV absorbers	BioSmart Reverte Plastigone	Mamin et al., 2023
Combination of dyes and pigments with /without metal oxo-additives / organometallics	Regulation of light absorbance; Long term stabilisation; Catalyst; Photosensitizing additive	Organic peroxides, organic hydroperoxides (e.g., tert-butyl hydroperoxide, cumene hydroperoxide), organic azo compounds (e.g., 2-azo-bis-isobutyronitrile), metallo-organic compounds, organic materials which undergo facile autoxidation, organic photosensitizers, organic dyes (Acridine Orange, Acridine Yellow); Ferrocene	Various patents	Mamin et al., 2023
Mineral fillers	UV protector; inhibitor of lactone and hydroperoxide formation	Carbonates (e.g., CaCO <sub>3</sub> ), nephelinesyenite, talcum, Mg(OH) <sub>2</sub> , aluminium trihydrate, diatomaceous earth, mica, cristobalite, and calcined clay.	Various patents	Mamin et al., 2023
TiO <sub>2</sub> -containing additives Combination of ZnO and TiO <sub>2</sub> .	Photo-absorption; Photo-catalysis; Photo-degradation acceleration	Nanoclays montmorillonite, kaolinite, silicon, silica polyhedral oligosilsesquioxanes hydroxyapatite, metal, and metal oxides (e.g., TiO <sub>2</sub> + PVA).	Various patents	Mamin et al., 2023
Aggressive species as prodegradants	Utilised to try to drive further degradation of microplastics arising from the oxo-degradation	Nitric acid, hydrochloric acid, sulfuric acid	Literature	Mamin et al., 2023

We note that the 2019 EU ban on oxo-degradable polymers has changed the landscape significantly. There has been a reduction in patent filings related to this class of plastics, and patents filed post 2019 have, in general, been extensions of existing patents, or were focussed on new additive blends that claim to control the degradation process more precisely or combination of PAC polymers with other materials to enhance degradability. There has been a growing focus on creating PAC polymers from bio-based and renewable sources, and a shift towards plastics that degrade under home composting conditions rather than degradation under industrial composting conditions (which requires temperatures > 50 °C, moisture >60 %, continuous oxygen supply and a microbial community). For example, NuPlastiQ material is formed from renewably sourced components (e.g., starch and glycerin), which are currently relatively inexpensive (e.g., US\$ 2.5 - 4 / kg, Bailey, 2024) in comparison to the other polymeric materials included in the blend (e.g., Polybutylene adipate terephthalate (PBAT, US\$ 3-6 / kg) and Polylactic acid (PLA, US\$ 2-5 / kg)) (Patent WO2024091912A2). At least some of the components used to produce the PBAT (e.g., butanediol, adipic acid, terephthalic acid) or PLA (e.g., lactic acid) may also be formed from renewably sourced components. Additionally, composite blends of PBAT (or another similar polyester) with PLA and a carbohydrate-based polymeric material have also been reported (Patent US11359088B2) to enhance degradation. While PLA alone is not compostable under home composting conditions (e.g., temperature of 28°C), but when blended in the manner described in the patent, it is claimed to be compostable under home composting conditions.

## 2. The environmental degradation of PAC plastics

The 2019 HSAC review of oxo-degradable plastics noted that: “there are surprisingly few published studies in the literature of systematic, replicated ‘field trials’ of oxo-degradable plastics in which specimens are monitored for breakdown and/or biodegradation under various naturally fluctuating conditions of temperature, light and moisture such as in soil, on soil surfaces, above ground, in fresh or sea water over prolonged periods (many months or years)”.

It is technically challenging to definitively confirm polymer / PAC plastic degradation in soils, especially since standard soil degradation tests (e.g., OECD 310 (2014) Ready biodegradability - CO<sub>2</sub> in sealed vessels (Headspace test) are indirect measures of biodegradation, and do not ask for direct (analytical) confirmation of (polymer) degradation. Soil degradation tests were originally developed for small molecules and thus assume mineralisation (by soil microbes) to CO<sub>2</sub> and H<sub>2</sub>O and assimilable forms of biomass and/or minerals. Similarly, more recently developed standard methods (such as ISO 17556:2019) rely on proxy measurements of oxygen demand in a respirometer or the amount of CO<sub>2</sub> evolved, and assess biodegradation of the test polymer relative to a reference material (such as microcrystalline cellulose which must reach 60% degradation at the plateau phase or by the end of the experiment) with the test polymer being required to reach 90% of the degradation of the reference material according to REACH Annex XVII (EU, 2023), rather than confirming the fate of the plastic in the soil through analytical

measurements. Complete understanding of the fate of the plastic within the system, to confirm complete polymer degradation would require use of isotopically labelled plastic ( $^{13}\text{C}$  or  $^{14}\text{C}$ ) in the standard degradation test and tracing of the fate of the stable or radioactive isotopes through the system via a complete mass balance. Additionally, methods for *in situ* analysis such as pyrolysis gas chromatography mass spectrometry (Py-GC-MS) are emerging but have yet to be validated for use with complex environmental samples such as soils and with PAC plastics (see the comprehensive review by Seeley and Lynch, 2023).

In the period since 2019, several studies on the degradation of PAC plastics have been published, mostly under controlled laboratory conditions (e.g., accelerated UV and thermal weathering in chambers), and a few under realistic environmental conditions (e.g. Moreira et al, 2021; Theobald et al, 2024). These studies evaluate aspects of physical-chemical changes and biodegradation of PAC plastics. Some key findings from studies conducted under realistic environmental conditions of relevance to the scope of this review are summarised in Table 2. While the overall weight of evidence points to PAC plastics being capable of faster physical-chemical degradation than the base polymers under laboratory UV and thermal ageing, there appears to be no clear agreement between published studies about the extent of the increment in degradation provided by the addition of pro-oxidant additives.

Additionally, there are significant concerns as to whether the controlled conditions of lab studies reported to date can be extrapolated to the complexity and variability of real environmental conditions. This is partly due to methodological weaknesses in the reported studies (e.g., failure to study the base polymer as a negative control), and partly because findings between different studies vary considerably due to differences in the polymers utilised, differences in the pro-oxidant additives utilised, differences in the test conditions applied and use of different test guidelines for the studies with some utilising ASTM standards (e.g., ASTM D6954-18), others utilising ISO 14855-2:2018, and to date none utilising the recent PAS 9017:2020 method which attempts to specify conditions in the open environment to which fugitive (littered) plastic is exposed to during the degradation and biodegradation process.

A well-conducted field study in New Zealand (Theobald et al, 2024) provides evidence that artificial ageing by exposure to ultraviolet (UV) radiation and heating is not a reliable model for natural degradation processes. This is consistent with the observation of another study (Moreira et al, 2021) that more research is required to assess the validity of correlations between laboratory accelerated and outdoor test methods. In summary, while the field trial studies published since 2019 have improved our understanding to some extent, the overall weight of evidence does not suggest any firm basis to deviate from the view of the previous HSAC review on this issue.

**Table 2: Key studies of fate of oxo-degradable plastics under realistic environmental conditions since 2019**

Reference	Strengths/weaknesses	Comments
Abed et al, 2020	Field study using polyethylene (PE) as a negative control. Samples were supermarket bags so the PE in OXO-PE and unamended PE bags likely not identical. Not conducted in accordance with any standard.	Field study examining degradation of OXO-PE and PE (as negative control) bags at two depths (2m and 6m) in the Arabian Gulf for 20 days and 80 days. No pre-ageing undertaken. Data not dramatically different for the two materials but suggests degradation of OXO-PE more extensive than PE.  HSAC notes that assessment of degradation in seawater is not predictive of fate in soil, as marine microbiota have evolved to degrade crude oil over decades.
Heimowska, 2023	No negative control – i.e., fate of unmodified PE not studied.	Studied degradation of Oxo-PE, under natural weathering in air and freshwater (in Poland) for 48 months. Oxo-PE displayed little degradation in freshwater, but was more vulnerable to environmental weathering in air and was completely destroyed after 45 months. Degradation of oxo-PE in natural environments required longer than the 24 months declared by the manufacturer.
Hill et al, 2021	Includes unmodified PE as negative control. Lacks replicate measurements of Molecular Weight (Mw) as required by PAS 9017. Also, starting Mw values for PAC containing sample were 35-43% lower than control before any weathering. This difference in properties makes direct comparison difficult.	Compares testing of oxo-degradable PE under standard lab conditions (PAS 9017:2020) and under controlled (ASTM D1435 20) field conditions in Florida. Temperate accelerated UV-weathering cycle over 14 days approximated to 90 days outdoor exposure in Florida for the PE film studied. Oxo-PE slightly more degraded (greater Mw loss) than control over full duration of experiment but noting the lower initial Mw of the PAC sample.
Mastalygina et al, 2023	Includes unmodified PE as negative control. Also, biodegradable polyester samples as positive control.	Open-air soil test conducted in Moscow (summer). Accelerated lab weathering test. Authors concluded that over the studied period of three months, oxo-LDPE did not degrade appreciably (0.3-2.5% mass loss). Results indicate resistance of oxo-LDPE to biological degradation without preliminary polymer oxidation. By comparison, biodegradable polyester underwent 13.9-15.4% mass loss and base PE showed zero degradation, as expected.

Reference	Strengths/weaknesses	Comments
Moreira et al, 2021	<p>Includes unmodified PE as negative control in tests conducted in S. France. Does not include negative control for tests in Florida. Lacks replicate measurements of molecular weight (Mw) as required by PAS 9017. The carbonyl index (CI) of the 17µm sample containing the PAC additive after 120 days of outdoor exposure in S. France was 0.62, markedly below the 1.0 threshold specified in PAS 9017. However, the same sample met the Mw criteria of PAS 9017 after 120 days.</p> <p>In contrast, following laboratory weathering, both Mw and CI criteria were met after roughly the same exposure time. This may imply different oxidative pathways occurring in laboratory and outdoor weathering.</p>	<p>Experimental study examining degradation of oxo-PE in outdoor exposure experiments (ASTM D1435-20) in S. France (120 days) and Florida (90 days). Also examined degradation under lab accelerated weathering (PAS 9017). Oxo-PE &gt;&gt; Mw loss (~97% cf 25%) than non-modified PE control under lab tests. In S. France tests, figures are 94% cf ~65% after 120 days.</p> <p>HSAC notes that both test sites have higher UV radiation and temperatures than UK and Northern latitudes, meaning that results may not be transferrable. Definite data showing degradation in conditions equivalent to the UK is lacking.</p>
Morrison et al, 2019	<p>Included non-modified polypropylene (PP) and PE products as negative controls. Does not appear to have been published in a peer-reviewed journal.</p>	<p>Compared non-modified PP and PE with oxo-containing equivalents (oxo-PP &amp; oxo-PE) under field weathering on an Arizona roof under dry, hot (max 45°C) conditions. Structural integrity of all samples except oxo-PP compromised. Concluded commercially available oxo-degradable plastics did not degrade at an accelerated rate compared to base polymers.</p>
Odobel et al, 2021	<p>Aquarium studies not really field conditions – though directly linked to the Mediterranean. Moreover, UV and thermal ageing prior to seawater immersion was conducted in a lab. Used base PE as negative control.</p>	<p>Experimental study that compared base PE with oxo-PE, both unaged and subjected to accelerated UV weathering (ASTM D5208) and thermal ageing at 70 °C (ASTM D5510). Samples then subjected to weathering in seawater in aquaria.</p> <p>Clear evidence seen of biodegradation of artificially aged oxo-PE in seawater. Signs of biodegradation visible after 1 month. No biodegradation observed for unaged PE, aged PE, or unaged oxo-PE.</p>

Reference	Strengths/weaknesses	Comments
Rose et al, 2020	Lab based study of biodegradation conducted on LDPE (negative control) and oxo-LDPE samples subjected to accelerated UV ageing in the lab. Authors note their findings require validation with naturally aged samples.	Data suggest artificially UV-irradiated samples of oxo-LDPE 90-fold more biodegradable by the soil bacterium <i>R. rhodochrous</i> than equivalently aged base LDPE. This correlated with oxo-LDPE reaching a lower molecular mass more quickly. Both unaged LDPE and oxo-LDPE showed limited biodegradation. Data show lengthier UV exposure necessary for biodegradation of conventional LDPE but impairs biodegradation of oxo-LDPE.
Song et al, 2023	Includes base HDPE as negative control and polylactic acid (PLA) and starch-based products as positive controls.	Field experiment in China, evaluating degradation of three alternative degradable plastics (including oxo-HDPE) and a traditional plastic used as peanut crop mulches. Oxo-HDPE 7.4-7.9% was degraded after 120 days. Base HDPE was not degraded, but PLA and starch-based films underwent ~60 and ~90% degradation, respectively.
Theobald et al, 2024	Field-based study. Base LLDPE used as negative control. Effects of field exposure examined for both: (a) samples subjected to standard (ASTM) lab-based accelerated UV ageing, and (b) samples not subjected to lab weathering. Sample thickness 4 mm, which differs from that found in e.g., shopping bags. Compared effects of artificial ageing with natural (seawater immersion) ageing.	Examined fate under submersion in water at depths of 20-60 cm in 3 New Zealand sites over 1 year. Examined oxo-LLDPE and base LLDPE. Lab UV-aged and non-aged samples tested. While lab UV ageing produced substantial effects on oxo-LLDPE (much greater than for base LLDPE), seawater immersion exerted only limited impact on oxo-LLDPE and LLDPE, whether aged or unaged. Suggests: (a) degradation of oxo-LLDPE did not occur under natural conditions; and (b) that artificial ageing may reasonably mimic changes which some plastic properties undergo in aquatic environments, it is generally not a reliable model for natural degradation processes.

Reference	Strengths/weaknesses	Comments
Vazquez et al, 2019	Used base LDPE, HDPE, and PP as negative controls.	Degradability of oxo-LDPE, oxo-HDPE and oxo-PP augmented studied under both natural (exposed to normal light at room temperature for 4 years) and UV accelerated aging (lab over 5 days at 70 °C for some of that period). Oxo-polymer degradation accelerated compared to base polymer under same conditions. However, molecular weights after aging insufficiently low to guarantee biodegradation by microorganisms.

### 3. The environmental and human toxicity of PAC plastics and their degradation products

The 2019 HSAC review of oxo-degradable plastics noted that “It is a struggle to find information in the scientific literature on whether oxo-degradable plastics themselves have harmful toxic properties”. The review also noted that some types of oxo-degradable plastics contain metal complexes with different quantities of Fe, Mn, Cu and Ni, which (if dispersed in the aquatic environment) may contribute to the overall environmental risk associated with metal contamination. The review of the scientific literature published since 2019 confirmed the limited knowledge of the potential ecotoxicological effects of oxo-degradable plastics. The paragraphs below summarise the new toxicity studies published between 2019 and October 2024.

In line with the ecotoxicological hypothesis provided in the 2019 HSAC Review, Schiavo et al. (2020) assessed the effect of leachates from various polymers with pro-oxidant additives (polyethylene, PE; polypropylene, PP; polystyrene, PS) on different test organisms; specifically, luminescent bacteria (*Vibrio fischeri*) (endpoint: bioluminescence inhibition), plants (*Sorghum saccharatum*, *Lepidium sativum*, *Sinapis alba*, and *Vicia faba*) (endpoints: growth, germination, roots elongation, chromosomal and DNA damage), and crustacean (*Daphnia magna*) (endpoints: immobilisation, reproduction).

The authors reported the following results:

Bacteria:

- All leachates induced a statistically significant inhibition (approximately 50%) of *V. fischeri* bioluminescence after 5, 15, and 30 minutes in all treatment groups.

Plants:

- L-PEa and L-PSa showed no toxic effects on tested plants. On the other hand, L-PPa was non-toxic for *L. sativum* and *S. alba*, but exerted a negative effect on germination and root elongation of *S. saccharatum*. The authors speculated that the different effects observed across species could be related to the differences in cell wall structure, which in turn may have an impact on permeability, metal binding capacity, and metal tolerance. The authors claimed that *S. alba* and *S. saccharatum*

germination index was strongly correlated with most metals, while plant root elongation seemed linked to  $Ti^{2+}$ ,  $Zn^{2+}$ , and  $Cr^{2+}$ ; however, the statistical basis underlying this observation is unclear.

(Note: Vazquez-Morillas et al., (2016) reported that biodegradation products of polyethylene films containing an oxo-degradable additive did not have any effect on the germination and development of tomato plants and grass seeds).

Daphnia:

- No effects on immobilisation/mortality were observed after 48 hours of exposure. On the other hand, this endpoint was affected after 21 days of exposure to the two highest concentrations of L-PPa and L-PSa. The effects on reproduction appeared to be different across treatments. The authors reported that both inhibitory and stimulatory effects for L-PPa and stimulatory effects for L-PEa. However, in some cases, the considerations provided in the text do not appear to match the results provided in Figure 2 of the manuscript (e.g. the figure shows a strong reduction in the number of neonates induced by L-PEa compared to control, whereas the text reports a stimulatory effect).

By integrating this data, the authors concluded that all the tested oxo-degradable polymer leachates (PE, PP, PS) exerted some effects on the tested organisms (with *D. magna* reproduction appearing to be most sensitive endpoint), proposing a ranking of toxicity where PE > PS > PP. They also concluded that “the oxo-degradable additive presence could not be considered the main factor responsible for the measured toxicity” and that the study provided evidence of an enhanced toxicity (compared to the equivalent virgin polymers evaluated by the same authors in a previous study (Schiavo et al. (2019)) “probably ascribable to a higher metals release”.

One important consideration concerning this study is that the environmental relevance of the leachate samples prepared in the study is unclear. For example, the authors tested different dilution percentages of the leachate (e.g. 100%, 75%, 50%), but it is unclear how that relates to the dilution factor expected to occur in the real-world environment, and what the expected mobility of released metals would be in different environmental matrices. Overall, a better characterisation of the exposure aspects of the problem would allow a more precise estimation of the environmental and ecotoxicological risk.

In a different study, Sable et al. (2020) investigated the ecotoxicological effects of degradation products of PP film samples (containing Co stearate as the pro-oxidant) produced after a sequence of abiotic (i.e. accelerated weathering) and biotic treatments. Specifically, the authors tested the effects of degradation products on microbial growth, plant growth (Mung bean and wheat plants), earthworm survival. The data indicated that the treatment did not induce adverse effect on any of the assessed endpoints.

Beyond these two studies, no other ecotoxicity evaluations were identified in the published literature between 2019 and October 2024. Overall, it is noted that establishing the direct ecotoxicological effects of the degradation products of oxo-degradable plastics is challenging due to the differences between laboratory set up and real-world conditions in which the degradation take place. This updated review confirms the limited understanding

of the ecotoxicological impact of PAC plastics and their degradation products. This knowledge gap could be mitigated by gaining a more systematic and quantitative understanding of the contribution of hazardous materials dispersed in the environment during the degradation process to the overall environmental exposome.

## 4. Policy considerations and remaining knowledge gaps

A notable feature of the literature post 2019 is that there is still a lack of controls in many of the studies, that renders their data of low value. There is some evidence that different oxidative pathways occur in laboratory and outdoor weathering, suggesting that the accelerated ageing observed in the laboratory may not be as predictive of real fate as would have been hoped.

The addition of starch and other biodegradable components into blends of non-degradable polymers can appear to make the polymers degrade more effectively, but there are concerns that this masks the non-degradation of the polyolefin component of the blend.

Several review and commentary papers noted that “Oxo- and semi-degradable polymers streamline the creation of microplastics rather than accelerating biodegradation” (Barron and Sparks, 2020) or that “the degradation of oxo-degradable plastics produces biologically recalcitrant microplastics and low molecular weight organic molecules, which can end up in leachates and potentially contaminate the environment. The introduction of the pro-oxidants into the plastics can also increase the polymer’s level of ecotoxicological risk.” (Kim et al, 2023). The review for the Scottish government noted that “it is the rate of degradation in a specific environment i.e., the length of time for completion of degradation, which is important. The longer an oxo-biodegradable plastic product remains in a given environment, the greater chance of increased environmental impact (such as through the persistence of small fragments /microplastics)” (Devalla, 2022).

A new specification standard, PAS 9017:2020 was released by the British Standards Institution as a specification requirement for the biodegradability of polyolefins in an open-air terrestrial environment which is applicable to PAC / oxo-degradable plastics. Little information is available on the adherence of PAC / oxo-degradable plastics to this new standard based on the review performed (Devalla, 2022). Similarly, limited evidence was found for compliance of PAC / oxo-degradable plastics to the standard EN 17033:2018 specifically for biodegradable mulch films (Devalla, 2022).

The results reported by Schiavo et al. (2020) were cited by Moreno et al (2023) to support the claim that metals released from oxo-degradable plastics may induce adverse effects in the environment. This paper was a non-experimental paper focused on false biodegradability claims related to single-use plastic utensils in Brazil. In response to Moreno et al. (2023), the commentary by Ojeda and Baciú (2024) argued that oxo-biodegradable masterbatches must not contain metals at levels above those permitted by the US Environmental Protection Agency or by the EU Directive 94/62/EC. However, here we note that the regulations on the levels of heavy metals allowed in packaging material

may not be fully appropriate for a scenario where such material is completely degraded in the environment, which implies that the whole metal load would be directly dispersed in environmental matrixes. In the same commentary, Ojeda and Baciu (2024) commented that “ASTM D6954 requires the material to be tested for eco-toxicity, according to the OECD Standards”. Here we note that the collation of such regulatory ecotoxicity data, if available, could contribute positively to the scientific and regulatory debate concerning the ecotoxicological effects of oxo-biodegradable plastics addressing - to some extent – the current data gap.

## 5. Conclusions regarding the current state of knowledge regarding PAC plastics

While field trial studies published since 2019 have improved our understanding to some extent, the overall weight of evidence **does not suggest any firm basis to deviate from the view of the previous HSAC review** that while oxo-degradable plastics appear capable of faster physical-chemical degradation than the base polymers under laboratory UV and thermal ageing, the extent of the increment in degradation provided by the addition of pro-oxidant additives remains unclear. Moreover, the evidence of the most recent well-conducted field study is that laboratory ageing experiments are not reliable models for natural degradation processes.

To definitively address the question of how completely PAC plastics degrade in soil environments, HSAC recommends that studies are performed utilising isotopically labelled plastics to definitely demonstrate whether the evolved CO<sub>2</sub> derives from the plastic or from soil organic matter, and that the potential for residual microplastics in the soil is assessed utilising Py-GC-MS analysis at various timepoints during and at the end of the respirometric test.

## Glossary of terms

**Biodegradation:** The breakdown by purely biotic means of a substance. This process is carried out by bacteria or fungi. This does not imply anything about the rate, or completeness of the process.

**Biotransformation:** The chemical conversion of substances by living organisms or enzyme preparations.

**Degradation:** The breakdown by either biotic or abiotic means of a substance

**HDPE:** High density polyethylene which is a form of PE with a density of greater or equal to 0.941 g/cm<sup>3</sup> and has a low degree of branching. Used in items like bottles, toys and water pipes.

**LDPE:** Low density polyethylene which is a form of PE with a density range of 0.910 - 0.940 g/cm<sup>3</sup> containing both short and long-chain branching. Can be used in containers, plastic bags and film wrap.

**LLDPE:** Linear low density polyethylene which is a form of PE with density of 0.915–0.925 g/cm<sup>3</sup> and contains significant numbers of short branches. Transparent and robust, it is often used in agricultural films and bubble packaging.

**Mineralisation:** This is where the original substance is converted to simple molecules like CO<sub>2</sub> and H<sub>2</sub>O. Note that unless the Carbon in the plastic is labelled (<sup>13</sup>C or <sup>14</sup>C) it is not possible to confirm the source of C in any evolved CO<sub>2</sub> as being from the plastic rather than from soil organic carbon.

**Oxo-biodegradable plastic:** Poorly defined term that may reflect the claim that oxidising agents and fragmentation will lead to biodegradation or the presence of other agents that specifically stimulate biodegradation.

**Oxo-degradable plastic:** A plastic (usually a polyolefin) containing agents which help to catalyse oxidation reactions to weaken and fragment the plastic. The industry would now prefer to use the term ‘thermo- or photofragmentable plastics’.

**PAC Plastic:** Pro-oxidant additive containing plastic (another description of oxo-degradable and oxo-biodegradable plastic, as well as those containing additives which lead to “biotransformation”).

**PE:** Polyethylene is a classic long chain CH<sub>2</sub>-CH<sub>2</sub>-CH<sub>2</sub> polymer.

**Polyolefins:** Family name for simple plastic polymers such as PE and PP. These are often associated with films, packaging, bags and containers.

**PP:** Polypropylene a polymer of CH<sub>2</sub>-CH(CH<sub>3</sub>)-CH<sub>2</sub> with a density between 0.895 and 0.92 g/cm<sup>3</sup>. Applications include bottles and containers.

**Prodegradant:** General term for an additive present in the plastic which promotes degradation (abiotic or biotic), typically a metal salt.

## References

- Abed, R.M.M., Muthukrishnan, T., Al Khaburi, M., Al-Senafi, F., Munam, A., Mahmoud, H. (2020) Degradability and biofouling of oxo-biodegradable polyethylene in the planktonic and benthic zones of the Arabian Gulf. *Marine Pollution Bulletin*, 150, 110639. <https://doi.org/10.1016/j.marpolbul.2019.110639>
- Ammala, A., Bateman, S., Dean, K., Petinakis, E., Sangwan, P., Wong, S., Yuan, Q., Yu, L., Patrick, C., Leong, K.H. (2011) *An Overview of Degradable and Biodegradable Polyolefins*. Elsevier Ltd.: Amsterdam, The Netherlands, 36, ISBN 2008006492.
- Bailey, J. (2024) Cost Comparison of Biodegradable Materials: What You Should Know. <https://planetpristine.com/sustainable/products/cost-comparison-of-biodegradable-materials/> (Accessed August 2024)
- Devalla, S. (2022) Review of evidence on Oxo-Degradable plastic products. <https://www.hutton.ac.uk/sites/default/files/files/publications/Review-evidence-on-Oxo-biodegradable-Plastic-Products-SDevalla.pdf> (Accessed June 2024)
- Dintcheva, NT. (2024) Overview of polymers and biopolymers degradation and stabilization towards sustainability and materials circularity. *Polymer*, 306, 127136. <https://doi.org/10.1016/j.polymer.2024.127136>
- European Commission, Directorate-General for Research and Innovation, Biodegradability of plastics in the open environment, Publications Office of the European Union, 2021, <https://data.europa.eu/doi/10.2777/690248>
- European Union (2023) *Annex XVII to Regulation (EC) No 1907/2006 of the European Parliament and of the Council concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) as regards synthetic polymer microparticles*. Available at: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32023R2055> (Accessed: 30 July 2024).
- Heimowska, A. (2023) Environmental Degradation of Oxo-Biodegradable Polyethylene Bags. *Water*, 15, 4059. <https://doi.org/10.3390/w15234059>
- Hill, G., Moreira, C., Huynh, F., Trufasila, A., Ly, F., Lloyd, R., Sawal, H., Wallis, C.J. (2021) Correlation of a Temperate UV-Weathering Cycle to Outdoor Exposure for the Determination of the Environmental Instability of Polyethylene Films Using HT-GPC Analysis. *Polymers*, 13, 591. <https://doi.org/10.3390/polym13040591>
- HSAC (2019): HSAC review of oxo-degradable plastics July 2019. Available from: [hsac-non-branded-oxodegradables.pdf \(publishing.service.gov.uk\)](https://publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/814247/hsac-non-branded-oxodegradables.pdf). Accessed June 2024.
- ISO 17556:2019 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. <https://www.iso.org/standard/74993.html>
- Mamin, E.A., Pantyukhov, P.V., Olkhov, A.A. (2023) Oxo-Additives for Polyolefin Degradation: Kinetics and Mechanism. *Macromol.*, 3, 477-506. <https://doi.org/10.3390/macromol3030029>

- Mastalygina, E., Abushakhmanova, Z., Poletto, M., Pantyukhov, P. (2023). Biodegradation in Soil of Commercial Plastic Bags Labelled as “Biodegradable”. *Materials Research*, 26, e20220164. <https://doi.org/10.1590/1980-5373-mr-2022-0164>
- Moreira, C., Lloyd, R., Hill, G., Huynh, F., Trufasila, A., Ly, F., Sawal, H., Wallis, C. (2023). Temperate UV-Accelerated Weathering Cycle Combined with HT-GPC Analysis and Drop Point Testing for Determining the Environmental Instability of Polyethylene Films. *Polymers*, 13, 2373. <https://doi.org/10.3390/polym13142373>
- Morrison, A., Paul Westerhoff, P., Thornton, T., Bi, Y. (2019). Thermal and Photo-oxidative Degradation of Commercially Available Oxo-degradable plastics. [https://ncni.net/sites/default/files/inline-files/E21\\_Morrison\\_2019ncniREU-1565520390530.pdf](https://ncni.net/sites/default/files/inline-files/E21_Morrison_2019ncniREU-1565520390530.pdf) accessed 18/06/2024.
- Odobel, C., Dussud, C., Philip, L., Derippe, G., Lauters, M., Eyheraguibel, B., Burgaud, G., Ter Halle, A., Meistertzheim, A.L., Bruzard, S., Barbe, V., Ghiglione, J.F. (2021) Bacterial Abundance, Diversity and Activity During Long-Term Colonization of Non-biodegradable and Biodegradable Plastics in Seawater. *Front. Microbiol*, 12:734782. <https://doi.org/10.3389/fmicb.2021.734782>
- Reddy, M.M., Deighton M, Gupta RK, Bhattacharya SN, Parthasarathy R. (2009) Biodegradation of oxo-biodegradable polyethylene. *J. Appl. Polym. Sci.* 111, 1426-1432. <https://doi.org/10.1002/app.29073>
- Rose, R-S., Richardson, K.H., Latvanen, E.J., Hanson, C.A., Resmini, M., Sanders, I.A. (2020) Microbial Degradation of Plastic in Aqueous Solutions Demonstrated by CO<sub>2</sub> Evolution and Quantification. *Int. J. Mol. Sci.*, 21, 1176. <https://doi.org/10.3390/ijms21041176>
- Sable, S., Ahuja, S. & Bhunia, H. (2020). Studies on Biodegradability of Cobalt Stearate Filled Polypropylene After Abiotic Treatment. *J Polym Environ* 28:2236–2252. <https://doi.org/10.1007/s10924-020-01762-3>
- Schiavo, S., Oliviero, M., Romano, V., Dumontet, S., Manzo, S. (2019) Ecotoxicological assessment of virgin plastic pellet leachates in freshwater matrices. *J Environ Account Manag* 6(4):345–353. <https://doi.org/10.5890/JEAM.2018.12.007>
- Schiavo, S., Oliviero, M., Chiavarini, S., Manzo, S. (2020). Adverse effects of oxo-degradable plastic leachates in freshwater environment. *Environ Sci Pollut Res* 27:8586–8595. <https://doi.org/10.1007/s11356-019-07466-z>
- Sciscione, F., Hailes, H.C., Miodownik, M. (2023) The performance and environmental impact of pro-oxidant additive containing plastics in the open unmanaged environment—a review of the evidence. *R. Soc. Open Sci.* 2023, 10230089. <https://doi.org/10.1098/rsos.230089>
- Scott, G. Initiation Processes in Polymer Degradation. *Polym. Degrad. Stab.* 1995, 48, 315–324. [https://doi.org/10.1016/0141-3910\(95\)00090-9](https://doi.org/10.1016/0141-3910(95)00090-9)
- Seeley, M.E., Lynch, J.M. Previous successes and untapped potential of pyrolysis–GC/MS for the analysis of plastic pollution. *Anal Bioanal Chem.* 2023, 415(15): 2873–2890. <https://doi.org/10.1007/s00216-023-04671-1>

Song, N., Wang, B., Liu, J., Wang, F., Wang, X., Zong, H. (2023) Is degradable plastic film alternative? Insights from crop productivity enhancement and soil environment improvement. *European Journal of Agronomy*, 149, 126882.

<https://doi.org/10.1016/j.eja.2023.126882>

Theobald, B., Risani, R., Donaldson, L., Bridson, J.H., Kingsbury, J.M., Pantos, O., Weaver, L., Lear, G., Pochon, X., Zaiko, A., Smith, D.A., Anderson, R., Davy, B., Davy, S., Doake, F., Masterton, H., Audrezet, F., Maday, S.D.M., Wallbank, J.A., Barbier, M., Abbel, R. (2024) An investigation into the stability and degradation of plastics in aquatic environments using a large-scale field-deployment study. *Science of the Total Environment*, 917, 170301. <https://doi.org/10.1016/j.scitotenv.2024.170301>

[US11359088B2 - Polymeric articles comprising blends of PBAT, PLA and a carbohydrate-based polymeric material](#)

Vázquez-Morillas, A., Beltrán-Villavicencio, M., Alvarez-Zeferino, J.C., Moreno, A, Martínez, L., Yañez, J.M. (2016). Biodegradation and Ecotoxicity of Polyethylene Films Containing Pro-Oxidant Additive. *J Polym Environ* 24:221–229.

<https://doi.org/10.1007/s10924-016-0765-8>

Vazquez, Y. V., Ressia, J.A., Cerrada, M.L., Barbosa, S.E., Vallés, E.M. (2019). Prodegradant Additives Effect onto Comercial Polyolefins. *J Polymers and the Environment*, 27, 464–471. <https://doi.org/10.1007/s10924-018-01364-0>

[WO2024091912A2 - Thermoplastic starch formulations with additives for performance enhancements](#)