

Hazardous Substances Advisory Committee

HSAC review of oxo-degradable plastics

July 2019

Summary

Largely in response to concerns over the unsightly consequences of visible littering, oxo degradable plastic forms were first invented in the 1970s. Current commercial oxo degradable plastics appear to be largely related to single-use polyethylene and polypropylene packaging and agricultural films. Within the parent material are embedded what are known as prodegradants which appear to be chiefly metal-organic complexes which help catalyse light and heat stimulated fragmentation of the polymer sheets. Thus, the intention is to speed up the natural fragmentation processes. Although this fragmentation into smaller and smaller plastic particles should be a helpful precursor to biodegradation, this has rarely been observed in a convincing manner outside laboratory conditions. There is no guarantee that oxo degradable plastics would receive the necessary pre-treatment of light and heat to start the fragmentation process. There is very little helpful literature available either on long-term field trials of biodegradation or ecotoxicity tests on a range of organisms for these plastics. Although there is worldwide concern over microplastic pollution of the environment, it remains the case that lethality to wildlife is more closely associated with large and intact plastic material. Nevertheless, a plastic which disintegrates more readily, may be at odds with the current strategy of controlling losses to the environment and might compromise the quality of recycled plastics.

Objectives of this review

In April 2019 Defra asked HSAC to review the topic of oxo-degradable plastics with special reference to:

- **The fate and environmental impact of oxo-degradable plastics in**
 - **the open environment, particularly marine; and**
 - **in the waste management system, including landfill, the recycling system or any other route;**
- **The plausibility of manufacturers' claims regarding the biodegradability of oxo-degradable plastics in light of this.**

The review was not meant to be exhaustive but to obtain an overview of the topic that reflects current knowledge.

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Background

1.1 Disposable or single-use plastics

Many of the advantages, conveniences and indeed environmental benefits of modern life brought to us over the past 70 years has been thanks to the employment of plastics. About 4% of our fossil fuels go towards plastics manufacture (Hopewell *et al.*, 2009). Single use items such as disposable packaging are believed to represent 37% of the approximately 300 million tonnes annual production of plastic www.plasticseurope.org (Hopewell *et al.*, 2009). It is now recognised that these disposable or single use plastics represent a real challenge in waste management and environmental pollution. However, such plastics are not without environmental benefits. Plastic films and packaging have provided health and safety benefits, reduced food waste and lowered the costs of transportation (Andrady & Neal, 2009). Such applications typically employ plastics from the polyolefin family (long chain polymers formed from alkanes) and include polyethylene and polypropylene. We use linear low density polyethylene (LLDPE) films as plastic sheeting in agriculture and both low and high density polyethylene (LDPE and HDPE) in single-use plastic bags. The benefits of these plastics come from their properties of durability, flexibility, water repellence and light weight. These very same properties mean they can end up being dispersed far and wide and have extremely poor biodegradation properties in the natural environment (Albertsson & Karlsson, 1990, Ohtake *et al.*, 1998). They have molecular weights from tens of thousands to hundreds of thousands, are hydrophobic and their repeating C-C and C-H bonds are largely resistant to microbial attack (Koutny *et al.*, 2006). Based on existing studies, it might be predicted that it would take 300 to 500 years for the complete breakdown of an LDPE or HDPE product (Table 1).

Table 1: Assessing the rate of breakdown of standard polyolefins

Reference	Form of plastic	Form of degradation	Medium	Incubation	Outcome
Albertsson & Karlsson (1990)	PE	mineralisation	soil	10 years	<0.2% CO ₂
Ohtake <i>et al.</i> (1998)	LDPE	Generation of low MW by-products	soil	32 years	Predict 300 years needed for complete degradation of film

Restrepo-Florez <i>et al.</i> (2014)	LDPE	mineralisation	Soil or mineral media	30 d to 10 years	0.1-7.5% weight loss
Restrepo-Florez <i>et al.</i> (2014)	HDPE	mineralisation	Soil or mineral media	1-2 years	0.4-1.6% weight loss

Largely in response to the amenity impact of plastic litter, there has been interest in the development of plastics which fragment more rapidly than the standard commercial forms (Koutny *et al.*, 2006, Ammala *et al.*, 2011). Efforts to design more readily degradable plastics go back to the origins of plastics. There have been a number of strategies proposed to make the polyolefins more degradable with the first patents apparently dating back to the birth of these plastics in the 1940s and many appearing in the 1970s (Ammala *et al.*, 2011). These usually involve the use of additives called prodegradants within the polymer.

There is a now a worldwide realisation that plastics, particularly those associated with single use applications, are accumulating in the environment due to their poor degradative characteristics. This is particularly notable in the marine environment (Thompson *et al.*, 2009), where the problem appears to be getting rapidly worse (Ostle *et al.*, 2019). The plastic litter includes intact material, large fragments, microplastics and nanoplastics (Andrady, 2017). Although intact material and large fragments have been shown to be lethal to animals and birds in the marine environment (Azzarello & Vanvleet, 1987, Gregory, 2009, de Stephanis *et al.*, 2013), it is microplastics which receive the most attention. There are currently 1,830 papers on Web of Science with the word 'microplastics' in the title. Since 2014, the growth in the number of such publications has been exponential. It is possible to find microplastics routinely in the gullets of fish and molluscs (EFSA, 2016, Horton *et al.*, 2018). There have been a range of compounds and mechanisms which have been suggested to make microplastics harmful to wildlife (Thompson *et al.*, 2009). Whilst not a toxic effect, microplastic ingestion can be an energetic drag on organisms (Bour *et al.*, 2018). Some have argued that it is the additives within some plastics, such as phthalates and bisphenol A that could convey toxicity (Thompson *et al.*, 2009). The key step in any risk assessment is the comparison of such effect concentrations with levels found in the environment. Generally, the view is that the environmental levels of microplastics in water environments remain below effect levels except in exceptional circumstances (Connors *et al.*, 2017, Adam *et al.*, 2019).

1.2. Theory of polyolefin degradation and biodegradation

To facilitate complete microbial mineralisation it is necessary for the material to be broken down into smaller particles, suggested to be at least a maximum of 5000 Da in order to pass a cell membrane (Reddy *et al.*, 2009) and for the introduction of hydrophilic groups to

increase water solubility (Ammala *et al.*, 2011). Thus, an oxo-degradable plastic might ultimately offer the potential for a more rapid disintegration into smaller particles and thanks to an increase in more hydrophilic groups, biodegradation might be encouraged.

Although the standard polyolefins are difficult to biodegrade, they can be disrupted by mechanical stress, high temperatures and most notably by photodegradation. In this case, the absorption of UV light leads, via the formation of CH-OOH hydroperoxide groups, to the generation of free radicals (short-lived molecules with an unpaired electron) which then react further with the polymer chain. These oxidation reactions can be detected as an increase in carbonyl groups ($R-(C=O)-R^i$) in the polymer, the proliferation of carbonyl groups increases its instability leading to further degradation (Ammala *et al.*, 2011). The mixture of photochemical and thermal abiotic degradation has been shown to lead to the formation of hydrophilic oligomers from the parent polymer (Eyheraguibel *et al.*, 2018).

This abiotic degradation mechanism is well known by the manufacturers and, ironically, it is common for plastics to contain additives to reduce propensity for this form of degradation. To this end, antioxidants are added to slow down abiotic degradation. These can be sterically hindered phenols to mop up free radicals and/or phosphites, phosphonites and thioesters to neutralise hydroperoxides. To reduce UV absorption, sterically hindered amine light stabilisers might be employed (Ojeda *et al.*, 2011).

2.0 Review of oxo-degradable plastics

2.1. Oxo-degradable plastics introduction

On the assumption that the disintegration of polyolefins into fragments is desirable in removing visible litter and may be a precursor to biodegradation, chemists have sought to enhance the natural photodegradation (and thermal breakdown potential) by adding molecules that speed up this natural process.

The most common prodegradant agents are the transition metals Fe, Co or Mn, introduced in trace quantities into the polymer product in a range of salts, fatty acid esters, amides, dithiocarbamates, ferrocene and metal oxides. It would appear that most of the current commercial oxo degradable plastics contain 1-5% by weight of a prodegradant including Fe, Ce, Co, Mn, Cu, Co or Ni within organic complexes (Ammala *et al.*, 2011). Fe is seen as being a particularly successful photo-inducer providing free radicals to start the abiotic reaction and Mn as catalysing further breakdown under heat (60 °C) ((Fontanella *et al.*, 2013). It would seem that temperatures above 40 °C are necessary for the heat activated reaction to be effective (Bonhomme *et al.*, 2003).

Other approaches include the introduction of organic groups that reduce stability in light, heat or moisture such as more carbonyl groups, oxo-hydroxy groups, unsaturated alcohols and esters, benzophenones, γ -pyrones, β -diketones, polyisobutylene, amines and peroxides. It is not clear if these organic prodegradants are present in the current commercial oxo-degradable plastics and no literature on their degradative potential in commercial products was found.

In the aspiration of stimulating microbial degradation as well as adding weaknesses to the plastic structure, substrates like starch may be added to the plastic (Lee *et al.*, 1991). Apparently the Reverte product from Wells Plastics Ltd contains micronized cellulose (Ammala *et al.*, 2011). These plastics may be called oxo-biodegradable plastics, although it is not clear if such terms have been standardised.

2.2. Oxo-degradable plastics and biodegradation

Both natural and oxo-degradable plastics degrade very slowly (Table 1 and 2). Given the very long timescales involved in biodegradation, from several to hundreds of years, it is common for researchers to simply demonstrate some level of biodegradation has happened rather than it being complete. Thus, a demonstration of degradation, or biodegradation being underway can be reported as an increase in carbonyl groups, a reduction in tensile strength, a reduction in molecular weight, additional CO₂ being generated or by the presence of microorganisms within the plastic structure itself (Table 2). These signals of partial degradation are different to the demonstration of the complete loss of the parent material.

Table 2: Assessing the degradation and biodegradation of polyolefins with prodegradants

(A) Examples of pre-treatment followed by incubation with microbial strain					
Reference	Form of plastic	Treatment	Medium	Incubation	Outcome
Albertsson <i>et al.</i> (1995)	LDPE with Fe prodegradant & starch	Heat then lab incubation with <i>Arthrobacter</i> spp	Lab medium and <i>Arthrobacter</i> spp	460 d	Microorganism consuming small MW by-products
Reddy <i>et al.</i> (2009)	LLDPE with or without prodegradant	14 d at 50-70 °C then 30 °C incubation with <i>P. aeruginosa</i>	Lab mineral medium and <i>P. aeruginosa</i>	42 d	Small improvement in biodegradation
Fontanella <i>et al.</i> (2010)	Variants of HDPE, LDPE and LLDPE with range of prodegradants	Photo-aging in lab and or 60 °C heat treatment then	<i>R. rhodochrous</i> in lab mineral medium	180 d	<i>R. rhodochrous</i> obtained energy from Fe and Mn prodegradant versions but not with Co

		incubation at 27 °C			
Fontanella <i>et al.</i> (2013)	Variants of PP with range of prodegradants	Photo-aging in lab and or 60 °C heat treatment then incubation at 27 C	<i>R. rhodochrous</i> in lab mineral medium	180 d	<i>R. rhodochrous</i> obtained energy from PP with Fe and Mn prodegradant versions but not with Co
Abrusci <i>et al.</i> (2013)	LDPE with Fe, Mn and Co stearate prodegradants	45-70 °C heat treatment for 9 d then irradiation for 10 d then culture incubation 30-45 °C	Different <i>Bacillus</i> spps and <i>Brevibacillus</i> in mineral medium at 30 or 45 C	90 d	Convincing abiotic changes with prodegradants present. Subsequent microbial incubation caused up to 45% mineralisation

(B) Examples of pre-treatment followed by incubation with soil or compost

Reference	Form of plastic	Treatment & pre-treatment	Medium	Incubation	Outcome
Fontanella <i>et al.</i> (2010)	Variants of HDPE, LDPE and LLDPE with range of prodegradants	Photo-aging in lab and or 60 °C heat treatment then soil or compost incubation at 25 or 60 °C	Soil or compost incubation.	352 d	Soil gave 9-12% mineralisation and compost 16-24% (after 317 d) for Fe and Mn additives, but Co caused inhibition
Jakubowicz (2003)	PE with different quantities of prodegradant	Different heat 50-70 °C and O ₂ for 70 d	Soil in lab at 29 or 60 C	70 d abiotic then 210 d	Abiotic degradation more influenced by heat than O ₂

		before soil incubation			level, then 60% mineralisation in soil in 210 d
Jakubowicz <i>et al.</i> (2011)	LLDPE with or without Mn prodegradant	40-70 °C then compost or soil incubation	Compost at 58 C or soil at 23 C	607 d	43% mineralisation in compost and 79% in soil after 607 d
Weiland <i>et al.</i> (1995)	LDPE with Co prodegradant	70 °C pre-treatment then incubation with cultures or composted	Lab or compost	83-150 d	Evidence of biodegradation
Husarova <i>et al.</i> (2010)	LLDPE with Mn & Fe prodegradant	70 °C oven 40-80 d then soil 25 °C or compost at 58 °C	Compost or soil	500 d	10-15% mineralisation in soil or compost
Ojeda <i>et al.</i> (2009)	HDPE and LLDPE with Mn prodegradant (d2W)	Held in open air for 1 year then composted at 58 °C	Air followed by compost	1 yr in air then 90 d composting	Prodegradant variety disintegrated/changed more readily in air and led to 12% mineralisation during composting
Chiellini <i>et al.</i> (2003)	LDPE & prodegradant from EPI	44 d at 55 °C heat pre-treatment then incubated in soil at 20 C or compost at	Soil or compost	525 d	50% mineralisation in soil and 80% in compost

		55 °C			
Ojeda <i>et al.</i> (2011)	HDPE and LLDPE with Co prodegradant vs same with antioxidants	Held in open air	air	270 d	Significant reductions in mass and increase in carbonyl groups with the prodegradant
Benitez <i>et al.</i> (2013)	PE vs LDPE & LLDPE with prodegradant	Heat 60 °C or air	air	260 d for air	Range of end-points show better degradation of the prodegradant variety

(C) Fate in the field following pre-treatment

Reference	Form of plastic	Treatment & pre-treatment	Medium	Incubation	Outcome
Corti <i>et al.</i> (2012)	LLDPE with prodegradant	Sunlight exposure then burial	soil	830 d	5% more degradation than control LLDPE over 27 months
Chiellini <i>et al.</i> (2007)	LDPE & prodegradant from EPI	70 °C heat pre-treatment then incubated in river	river	100 d after heat treatment	10-30% mineralisation
Yashchuk <i>et al.</i> (2012)	Compared simple PE with PE with range of commercial prodegradant	50 or 110 °C then UV pre-treatment then composted	compost	90 d	No long-term difference over 90d (24% biodegradation)

(D) Fate in the field without pre-treatment

Reference	Form of plastic	Treatment & pre-treatment	Medium	Incubation	Outcome
Musiol <i>et al.</i> (2017)	PE bag with Fe, Ce & Co prodegradant (TDPA)	4 m deep in real composting pile at 64 °C or water	Compost	70 d	Only minor changes
O'Brine & Thompson (2010)	PE bag with Fe, Ce & Co prodegradant (TDPA)	0.6 m deep in seawater	Sea water	280 d	Little discernible advantage in breakdown compared to standard PE
Napper & Thompson (2019)	HDPE control and two with prodegradants	Field study incubations	Kept in air or buried 25 cm in soil or 1 m deep in sea	830 d	One model of prodegradant had faster air disintegration than straight PE. Also more significant reduction tensile strength in soil and marine

2.3. Assessing the degradation and biodegradation potential of oxo-degradable plastics in laboratory environments

The evidence from the literature (Table 2 parts A and B) would suggest that provided a suitable pre-treatment has taken place, that is an exposure to natural or induced UV light and/or a thermal treatment, then some level of biodegradation of oxo-degradable plastics can be achieved subsequently under controlled conditions. The most complete biodegradation results were 45% mineralisation in 90 d using pure bacterial cultures in the laboratory (Abrusci *et al.*, 2013), 60% mineralisation in soil after 210 d (Jakubowicz, 2003) and 80% mineralisation in compost after 525 d (Chiellini *et al.*, 2003). All of these studies took place in controlled environments and involved quite extensive or aggressive pre-treatment conditions e.g. 70°C. Where comparative studies have taken place in the laboratory, the breakdown performance has been better than for the same plastics without prodegradants.

2.4. Assessing the degradation and biodegradation potential of oxo-degradable plastics in natural environments

There have been few studies where biodegradation has been studied in the field following or in the absence of pre-treatment (Table 2 parts B and C). The lack of reported studies on the potential for oxo-degradable plastics to biodegrade (alongside standard polyolefins) under realistic field situations is disappointing. From the limited evidence available, there is little consensus on the advantageous biodegradation of oxo-degradable plastic from realistic field studies. For example, over 830 d the prodegradant LLDPE was 5% more degraded than the control (Corti *et al.*, 2012) but Yashchuk *et al.* (2012) saw no difference over 90 d. Without pre-treatment and in sea water O'Brine & Thompson (2010) saw no advantage in breakdown between PE bags with and without prodegradants. In general, 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).

2.5. Toxicity and risks from oxo-degradable plastics

It is a struggle to find information in the scientific literature on whether oxo-degradable plastics themselves have harmful toxic properties. An agricultural tunnel plastic from Envirocare (believed to contain metal Fe, Ce and Co stearates) did not harm *Daphnia* or earthworms following OECD based tests (Bonora & De Corte, 2003).

The popular commercial oxo-degradable plastics including TDPI from EPI, Renatura from Nor-X industries, AddiFlex from Add-X Biotech and d2W from Symphony Environmental all contain metal complexes with different quantities of Fe, Mn, Cu and Ni (Ammala *et al.*, 2011). It should be noted that in a review of the relative risk of 71 different chemicals found in Britain's rivers, Cu came 1st (highest danger), Mn came 7th, Fe came 8th and Ni 12th in terms of risk (Johnson *et al.*, 2017). Consequently, the dispersion of more of these metals into the environment, particularly if they were to enter water courses would be unwelcome.

2.6 The case of the biodegradability of an alternative polymer, PVOH

As described in the introduction, single use plastics involved in packaging are typically from the polyolefin family. Plastic carrier bags being usually made from one of the varieties of polyethylene. This alternative product does not have the prodegradants present in oxo-degradable plastics, but proposes a different polymer altogether, that of polyvinyl alcohol (PVOH). Unlike PE, the PVOH is hydrophilic which should make biodegradation a more viable prospect (biodegradative enzymes being water-soluble themselves). The study by Boardman *et al.* (2017) describes carrying out a series of laboratory biodegradation experiments simulating industrial composting in both aerobic and anaerobic conditions, soil and marine environments. Biodegradation in most cases

being judged by carbon loss through CO₂ and CH₄ generation compared to controls. In addition, they tested the toxicity of dissolved plastic on aquatic invertebrates and algae.

In aerobic conditions PVOH did fragment but little or no biodegradation occurred. The most positive results were associated food or wastewater derived anaerobic digestion (better than LDPE), although this did not lead to complete breakdown in the time allowed. No marine biodegradation was noted, although incubation in soil for a year was inducing a structural change in the polymer as judged by infra-red absorbance. Dissolved PVOH film did not harm the alga or *Daphnia magna*. No harmful effects were noted when juvenile lobsters were fed PVOH mixed as microplastic as 20% of their food stuff other than a possible reduction in growth rate.

2.7 The European Commission report on oxo-degradable plastics, April 2017

The European Union has decided to restrict the use of oxo-degradable plastics (Commission, 2018). A report was prepared in 2017 which reviewed the topic of oxo-degradable plastics and the environment (Hann *et al.*, 2017) to help inform The Commission. This report started by reviewing the wide range of EU and international standards on the biodegradability of materials in environments from composting to wastewater, marine and soil. The majority of these tests require evidence of substantial biodegradation within one year. The review supported the position that oxo-degradable plastics would be subject to faster abiotic degradation compared to standard polyolefins. The report reviewed biodegradation in compost where the evidence was seen as contradictory but they acknowledged that the manufacturers association made no claims on the product being compostable. The report went on to examine the potential for oxo-degradable plastics to biodegrade in the open environment. The authors were somewhat optimistic in their analysis, although it was acknowledged that biodegradation rates would inevitably be very slow. They noted that the industry had no specific standard to meet which left the ground open to claims that may be confusing to consumers. With regard to landfill, the authors thought it safest to assume no significant biodegradation would occur. With respect to marine biodegradation, the authors had insufficient evidence to come to a conclusion, although they were pessimistic as to the likelihood of this occurring. The authors did not come to a definite conclusion on whether oxo-degradable plastics and their fragments would be harmful to the soil ecosystem. The preoccupation of the authors in this case was with Co prodegradants (they did not refer to Fe, Mn or Ce prodegradants). The authors also reviewed whether the fragmentation of oxo-degradable plastics would reduce harm to wildlife in the marine environment. The authors acknowledged the potential benefits of reducing lethal impacts of wildlife being entrapped in intact plastics. They recognised that the breakdown of plastics into microplastics would lead to wider exposure to different trophic levels and inevitably to humans. They speculated that some toxic chemicals in microplastics would have wider environmental impacts. The other components of the report were related to recycling and consumer issues.

3.0 Conclusions

3.1. General Observations

- Standard polyolefins will photodegrade to fragments if held in the light. However, it would appear that it is common for commercial polyolefins to contain antioxidants or UV blockers to slow this process down.
- Standard polyolefins biodegrade very poorly if at all.
- There are a range of prodegradant chemicals available which when present in oxo-degradable plastics could theoretically speed up abiotic degradation of polyolefins. However, it appears the current range of prodegradants (as of 2011) rely on metal-based complexes.
- There is evidence that given suitable pre-treatment, involving exposure to light and or heat, in the presence of oxygen, that oxo-degradable plastics undergo a series of changes including fragmentation and the formation of many carbonyl groups which could facilitate subsequent biodegradation.
- Following suitable pre-treatment involving exposure to light and/or heat the oxo-degradable plastics can act as a substrate for some bacterial species and be used as a carbon and energy source under laboratory conditions.

3.2. Weaknesses in our understanding

We only appear to have evidence on the fate of oxo-degradable plastics containing metal-based complexes and not for those with organic prodegradants. It is not clear if organic prodegradants are present in commercial products.

It would be useful to know if the incorporation of biodegradation promoters such as cellulose or starch offer benefits to the biodegradation of polyolefins.

There is no guarantee that discarded oxo-degradable plastics will receive sufficient light and or thermal pre-treatment before they enter waste disposal systems to facilitate degradation. It is not clear what this minimum desirable light and/or heat pre-treatment should be.

There are very few field studies on long-term degradation of oxo-degradable plastics with standard plastics under the typical fluctuating and diverse conditions.

3.3. Returning to the Defra questions:

- **The fate of oxo-degradable plastics in**
 - **the open environment, particularly marine;**

There are few studies on the degradation of oxo-degradable plastics in the natural environments of terrestrial, river and marine. To a large degree, the results depend on whether sufficient pre-treatment of UV exposure and or heat was applied before the environmental biodegradation study took place. This pre-treatment step did not happen with a recent soil and marine degradation study (Napper & Thompson, 2019). However, it is clear that the marine environment is not conducive to the abiotic degradation of oxo-

degradable plastics due to bio-fouling and sinking which reduce UV exposure whilst the low temperatures also reduce abiotic degradation (O'Brine & Thompson, 2010). In other words, the oxo-degradable plastics approach is not a solution to plastic litter once it is within the marine environment.

- **The environmental impact of oxo-degradable plastics in**
 - **the open environment, particularly marine;**

It would seem retrogressive to be introducing more metals into the terrestrial or freshwater environments, although the quantities involved are not clear, nor is it clear whether metals would indeed be released. However, it may be that some oxo-degradable plastic products since 2011 do not use metal complexes and do not have this deficit, but we do not have this product information.

The disintegration of plastic litter into microplastics will increase the chances of exposure to wildlife. This does not necessarily lead to bioaccumulation, since it is likely that microplastic particles will also be excreted. Except in cases of very high exposure, we do not yet have evidence that microplastics are or could be harming wildlife. This does not imply safety, simply that experiments showing serious impacts at environmentally relevant levels are not yet abundant in the literature.

Currently the strongest evidence for harm to wildlife is from intact or large fragments of plastic harming apex predators and omnivores (Azzarello & Vanvleet, 1987, Gregory, 2009, de Stephanis *et al.*, 2013). These effects are largely linked to entrapment and prevention of food ingestion leading to starvation. Such harmful impacts on these animals may reduce if plastics did reduce to small particles more quickly.

- **in the waste management system, including landfill, the recycling system or any other route;**

Ideally, all plastic, in both developed and developing worlds would be captured and treated inland, either recycled or used as an energy source. However, the mixture of oxo-degradable plastics with those plastics without prodegradants might potentially compromise the recycled product. In the developing world, in countries without refuse collection, landfill or recycling facilities, a high proportion of single use plastics end up in the ocean (Rhodes, 2018). It is clear that due to weaknesses in institutions and governance, this source of plastics is not going to be curbed soon (Dauvergne, 2018). In such cases, the breakdown of polyolefins that make up single use packaging, into smaller and smaller particles before they are carried to the sea might lead to a helpful reduction in lethal cases of entanglement and smothering.

Treatment via composting and heat, ensuring oxygen is present is an essential precursor to the oxo-degradable plastic biodegradation. Nevertheless, whilst composting might start the process, biodegradation remains a lengthy affair and so a compost product is still likely to contain plastic fragments. Studies of polyolefins in landfills show little detectable degradation over time (Hamilton *et al.*, 1995) and it would seem that oxo-degradable plastics do not show any improvement on this situation, at least from a one year study (Adamcova & Vaverkova, 2014). Most parts of a landfill are entirely anaerobic and this

would not permit the necessary oxidation needed for oxo-degradable plastics fragmentation.

- **The plausibility of manufacturers' claims regarding the biodegradability of oxo-degradable plastics in light of this;**

The literature describing controlled laboratory conditions would support the theory behind the biodegradability of oxo-degradable plastics. However, the evidence for convincing biodegradation under entirely natural conditions (outside the laboratory) is very sparse and much less clear. More realistic studies in a range of natural environments are strongly recommended to properly understand the long-term degradation and/or biodegradation of these plastics in the open environment over reasonable time periods. 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.

Avoiding the use of plastic packaging where possible and maximising the recovery and recycling of such plastics should remain the central planks of our management strategy.

Competing interests

The lead author has declared no competing interests.

Glossary

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

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

PAC Plastic: Pro-oxidant additive containing plastic (another description of oxo-degradable plastic)

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

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

Mineralisation: This is where the original substance is converted to simple molecules like CO₂ and H₂O

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

Prodegradant: General term for additive present in the plastic which promotes degradation (abiotic or biotic)

PE: Polyethylene is a classic long chain CH₂-CH₂-CH₂ polymer

HDPE: High density polyethylene which is a form of PE with a density of greater or equal to 0.941 g/cm³ 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/cm³ 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/cm³ and contains significant numbers of short branches. Transparent and robust, it is often used in agricultural films and bubble packaging

PP: Polypropylene a polymer of CH₂-CH(CH₃)-CH₂ with a density between 0.895 and 0.92 g/cm³. Applications include bottles and containers

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