

**Annex B**

# Updated Evidence and Literature Review on Oxo-degradable and Oxo-biodegradable Plastics

This work was commissioned by the Welsh Government (L01555).

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# 1. Definitions and general overview of ODPs

## 1.1. Definitions and abbreviations

- **ATR-FTIR:** Attenuated total reflectance – Fourier transform infrared spectroscopy. An analytical technique used to identify polymer types.
- **Biodegradation:** The microbial conversion of all organic constituents of a material to carbon dioxide, new microbial biomass and mineral salts under aerobic conditions, or to carbon dioxide, methane, new microbial biomass and mineral salts, under anaerobic conditions [1]. The final stage of biodegradation is referred to as **mineralisation**.
- **Biodegradable plastics:** A type of plastic which can be made from renewable or non-renewable (fossil) carbon sources and is intended to biodegrade more rapidly than conventional plastic but requires specific conditions [2]. The biodegradation of plastic is a ‘system’ property requiring a) material properties that allow for microbial conversion, **and** b) suitable conditions in the receiving environment (temperature, pH, microorganisms, moisture, etc.) such that biodegradation can take place [2, 3].
- **Compostable plastics:** A subset of biodegradable plastics. Industrially compostable plastics are designed to biodegrade in an industrial composting facility or anaerobic digestion plant with subsequent composting steps [4]. Biodegradable plastics can be compostable if degradation has been certified according to respective standards (e.g., EN 13432, EN 14995).
- **Degradation:** The chemical breakdown of bonds and functional groups of the polymer and/or associated additives through abiotic or biotic processes [5].
- **Fragmentation:** The physical breakdown of the plastic material into smaller particles. Whilst chemical degradation of plastic is an influencing factor for the fragmentation of plastic (e.g., by affecting the structural integrity of the material), other factors such as mechanical stress and environmental conditions play key roles in the fragmentation process. It is therefore essential to distinguish between physical fragmentation of the material and the chemical degradation [5].
- **HDPE:** High-density polyethylene. This is a fossil-carbon based polyolefin.
- **LDPE:** Low-density polyethylene. This is a fossil-carbon based polyolefin.
- **LLDPE:** Linear low-density polyethylene. This is a fossil-carbon based polyolefin.
- **MaPs:** Macroplastics are plastic fragments > 5mm [6].
- **MPs:** Microplastics are plastic fragments in the size range of 1 µm – 5 mm [6].
- **NPs:** Nanoplastics are plastic fragments < 1 µm [6].
- **ODP:** Oxo-degradable or oxo-biodegradable plastics.
- **Oxo-degradable plastics:** Plastic materials that include additives which, through oxidation, lead to the fragmentation of the plastic material into micro-fragments or to chemical decomposition [7]
- **PAC:** Pro-oxidant containing plastics that degrade in the open environment via oxidation and other processes [8]. Another term for ODPs.

- **PBAT:** Poly(butylene adipate-co-terephthalate). This is a degradable plastic made of adipic acid, 1,4-butanediol, and terephthalic acid.
- **PE:** Polyethylene. This is a fossil-carbon based polyolefin.
- **PP:** Polypropylene. This is a fossil-carbon based polyolefin.
- **SEM:** Scanning electron microscopy. An analytical technique used to ascertain particle size in the context of this report.

## 1.2. Overview of ODPs

During the production process of ODPs, pro-oxidant additives are incorporated into the fossil-carbon based polymer mix (often PE or PP). The exact constituents used in commercial pro-oxidant containing plastics are largely patented/proprietary; however the most commonly used pro-oxidants are transition metals, which are added to the polymer at up to 5% (w/w) [8, 9, 10]. The role of the additives is to accelerate oxidation of the plastic, resulting in an increase in low-molecular weight oxidation products (e.g., carbonyls), and ultimately in the breakdown of ODPs into low-molecular weight fragments. This stage requires oxygen and can be accelerated by exposure to UV light (photodegradation) and elevated temperature (thermal degradation). During this stage of degradation, the transition metal salt additives act as catalysts. The second stage involves microorganisms (e.g., bacteria, fungi), which assimilate the low-molecular weight products (biodegradation).

The terms oxo-degradable and oxo-biodegradable are used synonymously in industry, and **previous studies concluded there is no difference between the two, as both terms refer to pro-oxidant containing polyolefins [8, 9]. Recent studies reinforce this consensus [11, 12, 13].**

## 2. Executive summary

The Environmental Protection (Single-use Plastic Products (SUPP)) (Wales) Act 2023 stipulates a ban on single-use plastic items as covered in Section 2 of the Directive [14]. The ban also includes ‘oxo-degradable’ plastic products, due to concerns over their incomplete degradation (leading to microplastics pollution) and issues related to their end-of life management, such as recycling and composability.

This document builds on reviews previously commissioned by the Welsh Government [15], DEFRA [10, 16], and the Scottish Government [9], to provide an updated evidence review on oxo-degradable and oxo-biodegradable plastics (collectively referred to as ODPs).

Summary of the key findings of this report:

- Evidence that ODPs follow the same degradation behaviour shown under laboratory testing conditions when exposed in natural environments is lacking. This is particularly pertinent for environments with cool climates, such as those in Wales.
- The review of recent scientific literature published since 2023, directly aligns with the findings of previous reports. There is high potential for the persistence of larger fragments, microplastics, and nanoplastics in the natural environment and managed waste system.
- ODPs have been primarily designed to degrade in open-air conditions – where oxygen availability and UV light promote degradation; therefore, end-of-life options such as composting, recycling, and landfill are ambiguous. This complicates the end-of-life management of ODPs and could undermine sustainability efforts aimed at increasing material circularity, reuse, and recycling.
- ODPs share many environmental concerns with conventional plastics, however their propensity to fragment can increase their bioavailability, which, with a lack of transparency of their chemical composition and the potential for these to leach, raises additional concerns. There remains a paucity in knowledge regarding the long-term effects of ODPs, which prevents a complete assessment of their environmental impact.
- The current degradability standards are guidelines which lack pass/fail criteria and are not specification standards or certification of performance. Testing standards are not designed to replicate environmental conditions and therefore the extrapolation from laboratory findings to real-world, environmental scenarios should be avoided.

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### 3. Policy context

In response to concerns over the incomplete degradation of oxo-degradable and oxo-biodegradable plastics (and release of microplastics), and issues relating to their recyclability and composability, countries around the world have introduced regulations on ODPs (Table 1). ODP products are banned across Europe under the European Single-Use Plastic Directive (EU 2019/904) [7], in Switzerland [17], New Zealand [18], and in states across Australia [19, 20, 21]. Additionally, consultations are ongoing in Scotland [22] and Peru [23].

In 2019, the Welsh Government commissioned an assessment of the potential social, economic and environmental impacts of banning the supply of specific single-use plastic products in Wales [15]. The outcome of this research was used to develop the Regulatory Impact Assessment [24], which accompanied the introduction of the Environmental Protection (SUPP) (Wales) Act 2023 [14]. The initial schedule of prohibited products in the SUPP Act included a ban on all single-use products made of oxo-degradable or oxo-biodegradable plastics, also known as pro-oxidant containing (PAC) plastics.

**Table 1.** Summary of implemented and proposed legislation related to ODP/PAC plastics in different countries/regions. This summary is not an exhaustive list of legislation, and instead serves as an illustration of the geographic breadth of countries with bans on PAC plastics in place, or under development.

Country/ Region	Status of the legislation	Legislation details
Europe	Banned- since 2019	The <i>Single Use Plastics Directive (EU 2019/904)</i> [7] prohibits placing on the market certain single-use plastic items, including those made from oxo-degradable plastics.
Norway	Banned- since 2019	The <i>Single Use Plastics Directive (EU 2019/904)</i> [7] prohibits placing on the market certain single-use plastic items, including those made from oxo-degradable plastics.
France	Banned - since 2015	Banned since 2015, now also covered by the <i>EU SUP Directive (EU 2019/904)</i> [7].
Switzerland	Banned- since 2022	The <i>Ordinance on the Reduction of Risks relating to the Use of Certain Particularly Dangerous Substances, Preparations and Articles</i> prohibit placing on the market and use of oxo-degradable/PAC plastics [17].
New Zealand	Banned- since 2022	The <i>Waste Minimisation (Plastic and Related Products) Regulations 2022</i> ban the manufacture, sale or supply of plastics with pro-degradant additives [18].
New South Wales, Australia	Banned- since 2021	Under the <i>Plastic Reduction and Circular Economy Act 2021 No 31</i> [20].
South Australia, Australia	Banned- since 2022	Under the <i>Single-use and Other Plastic Products (Waste Avoidance) Act 2020</i> [19].

Western Australia, Australia	Banned – since 2023	Under Western Australia’s Plan for Plastics, Stage 2 [21].
Canada	Banned- since 2024	<i>Single-Use and Plastic Waste Prevention Regulation</i> [25] bans oxo-degradable plastics used for single-use products or packaging.
Hong Kong	Banned- since 2024	Oxo-degradable plastics are listed under the <i>Product Eco-responsibility (Amendment) Ordinance 2023</i> [26].
Scotland	proposed	[22, 27, 28]
England	proposed	[28]
Wales	proposed	Under the <i>Environmental Protection, Single-Use Plastics Product (Wales) Act 2023</i> [14].
Peru	proposed	Drafted under the <i>Decreto supremo que aprueba el reglamento tecnico sobre vajilla Y/O utensilios de mesa de plastico reutilizables</i> [Decree approving the technical regulation on reusable plastic tableware and/or tableware] 2025 [23].
Brazil	proposed	Drafted under <i>regulation PL 2524/2022</i> [29].
California, USA	proposed	The <i>State Assembly Bill AB-1290 (2023–24)</i> included a ban on PAC plastics; this passed through committees but was not adopted [30].
Queensland, Australia	proposed	Proposed under the <i>Waste Reduction and Recycling Act 2011</i> , Banned single-use plastic items – Review of Part 3A and 3AA [31].

#### **4. Objectives**

In line with the specifications laid out by the Welsh Government, the objectives of this review were two-fold. *REDACTED* and secondly, to collate scientific literature published since initial reviews were undertaken in 2023, to synthesise an updated evidence review on ODPs, with a special reference to:

1. The degradation of ODPs
  - a. in unmanaged natural environments,
  - b. in managed waste systems,
  - c. and the potential formation of microplastics during the degradation process.
2. The environmental impacts of ODPs in unmanaged natural environments and managed waste systems.
3. The assessment of the transferability of standardised testing of ODPs to real-world contexts.

This review was not meant to be exhaustive but to provide an updated overview of the current state of knowledge on ODPs, *REDACTED*

This review has focused only on ODPs, and a comprehensive comparison with other plastic types, e.g., compostable or biodegradable, has not been undertaken.

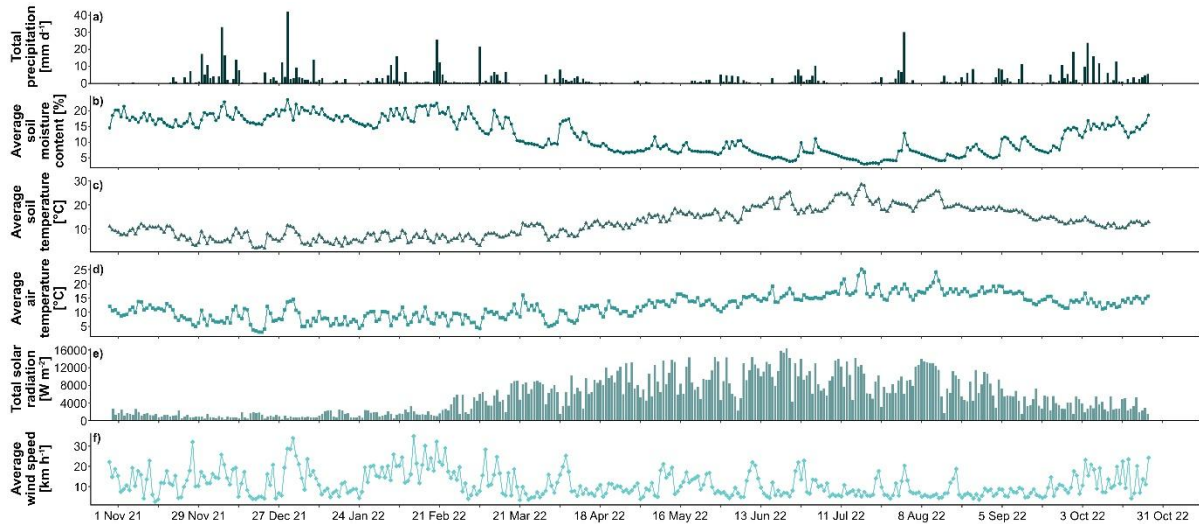
## 5. Updated evidence review: Degradation of ODPs in natural environments, managed waste systems, and their potential to generate MPs

### 5.1. Degradation of ODPs in natural environments

Scientific investigation into the degradation of ODPs in natural environments remains limited. Whilst the presence of pro-oxidant additives accelerates the chemical breakdown of the plastic in controlled testing conditions, these findings are not translatable to open environments due to the varied exposure conditions between the laboratory tests and open environments [8, 9, 16].

The additives act as catalysts for the oxidation of the polymer, thereby promoting chain scission, subsequently breaking the polymer chain into smaller low-molecular weight fragments. However, the degradation kinetics are highly dependent on environmental conditions (e.g., UV exposure, temperature) [8, 9, 16]. The majority of current degradation test guidelines use either hot, dry climates as a reference for testing conditions (e.g., Florida) or lack alignment with natural environmental conditions altogether [8, 16]. This poses a challenge when trying to evaluate the degradation of ODPs in the open environment, and when exposure conditions deviate from the test parameters. For example, Wales has an average annual temperature of  $10.03 \pm 0.13$  °C and precipitation of  $1584.02 \pm 84.64$  mm  $y^{-1}$  (average records from 2020-2024) [32] (Table 2); in comparison, the average annual temperature in Jacksonville, Florida, is 20.28 °C with total average precipitation of  $1289.05$  mm  $y^{-1}$  (average records from 1991-2020) [33].

Also, natural environments are heterogeneous, and environmental conditions vary over daily, seasonal, and annual cycles (Figure 1), whereas test guidelines are fixed at constant and optimal conditions for the entirety of the test exposure period. Additionally, standardised test guidelines also operate under the assumption that ODPs will be exposed to UV and natural weathering prior to incorporation into soil, sediment, or watercourses, priming the polymer for microbial assimilation. For example, the purpose of stage 1 in ASTM D6954 is to expose the ODP to UV in order to change the molecular weight of the plastics, i.e., initiating degradation [34]. The pro-oxidants added to the polymer mix will only fulfil their intended function under conditions with sufficient light and oxygen – if the material is immersed in soil or sediment, or submerged in water, the catalyst loses its functionality and will not aid in the degradation process [5]. It is unlikely that the plastic will experience sufficient exposure under natural scenarios and environmental conditions, which will subsequently hinder microbial degradation processes, resulting in the plastic remaining in the environment for a prolonged duration [8, 9, 10].



**Figure 1.** Environmental data across a 12-month period recorded at the Henfaes Research Centre, Abergwyngregyn, North Wales. a) Total daily precipitation; b) Average daily soil moisture content at 5 cm depth; c) Average daily soil temperature at 5 cm depth; d) Average daily air temperature; e) Total daily solar radiation; f) Average daily wind speed. Figure reproduced from [5].

**Table 2.** Comparison between average annual environmental data from Wales (2020 – 2024) and test conditions used during degradation testing in controlled settings. Values for Wales are expressed as mean  $\pm$  standard error. Values for test conditions are guidance values for optimal range.

	Unit	Wales	Test conditions
Average air temperature <sup>†</sup>	°C	10.03 $\pm$ 0.13	50 $\pm$ 3
Maximum air temperature <sup>†</sup>	°C	13.58 $\pm$ 0.17	53
Minimum air temperature <sup>†</sup>	°C	6.52 $\pm$ 0.16	47
Average soil temperature <sup>‡</sup>	°C	12.50 $\pm$ 0.02	58 $\pm$ 2
Average UV intensity <sup>‡</sup>	W m <sup>-2</sup>	114.64 $\pm$ 0.66	75.65 <sup>Δ</sup>
Average UV intensity (Oct-Mar) <sup>‡</sup>	W m <sup>-2</sup>	48.87 $\pm$ 0.49	n/a
Average UV intensity (Apr-Sep) <sup>‡</sup>	W m <sup>-2</sup>	175.57 $\pm$ 1.00	n/a
Total precipitation <sup>†</sup>	mm	1584.02 $\pm$ 84.64	0

<sup>†</sup> Data sourced from MetOffice historical data for Wales [32].

<sup>‡</sup> Data sourced from weather station located at the Henfaes Research Centre, Abergwyngregyn, North Wales.

<sup>Δ</sup> Value calculated based on UV range of 315-400 nm and exposure of 0.89 W m<sup>-2</sup> nm<sup>-1</sup>.

Recent laboratory studies found enhanced rates of degradation of pro-oxidant (cobalt and iron stearate) containing rubber after 8 weeks of thermal treatment at 65 °C, followed by 6 months of burial in a soil-compost mixture (ODP concentration 0.1% w/w), with no recorded effects on plant growth [35]. Similarly, a study focusing on pro-oxidant (cobalt and ferric stearate) containing PP reported increased oxidation and degradation after 3 months of natural weathering, and 74-77% mineralisation after subsequent 140 day soil-compost incubation, with no adverse effects on microbes and plants in follow-up ecotoxicity tests [36]. Degradation of ODPs (Polimerida, Mexico) is highest after both photo and thermal oxidation, in comparison to only a single oxidation method, suggesting that a combination of high temperatures and UV irradiance facilitates the rapid oxidation of ODPs [37]. Additionally, modifying the formulation of pro-oxidant agents by replacing the transition metal salts with benzoin, an organic compound which can be used as a photocatalyst [38], resulted in accelerated oxidation and flaking after 20 days of natural weathering, and 16% mineralisation at the highest benzoin concentration (1.5% w/w) after 120 days soil incubation [39]. Whilst this marks a development in terms of reducing the environmental metal burden through potential leaching, the degradation behaviour was comparable to that observed in previous reports, i.e., accelerated oxidation under abiotic degradation leading to fragmentation and brittleness of material with slow biodegradation rates, and thus it is not clear what effect this would have on the rate of generation and persistence of MPs/NPs, and other chemical leachates.

Recent work has highlighted challenges in translating laboratory results to the open environment context. Comparing the degradation of ODPs (Polymateria Ltd., UK) under artificial laboratory conditions and open-air environmental conditions in the UK (akin to littering) over 24 months, revealed that rapid fragmentation occurred in the laboratory, which was not observed in-situ. After 7 days of artificial laboratory degradation, ODPs had fragmented and after 28 days had formed MPs, whereas ODPs in the environment had some reduction in molecular weight but remained intact, with negligible degradation observed [40]. ODPs also showed no signs of biodegradation and performed similarly to conventional polymers under standardised biodegradability test conditions.

A greenhouse study, conducted with UK agricultural soil, found that ODP (Symphony Environmental Ltd., UK; d2w pro-oxidant) degradation in soil was slow, and inversely correlated with the ODP concentration, highlighting that biodegradation without prior abiotic degradation proceeds at a slow rate, and that accumulation of ODPs in soil could inhibit this process even more [41]. This study also reported a decrease in soil and plant health with increasing ODP concentration, which is particularly relevant for ODP residues in agricultural fields and waste management systems such as landfill, leading to a potential accumulation rather than steady degradation of these materials. The soil biodegradation of ODPs (pro-oxidant: Reverte™) has also been investigated in a laboratory <sup>13</sup>C incubation study, with 0.4% mineralisation in a soil mixture (0.8% w/w concentration) after 185 days [42]. This method assessed carbon mineralisation in the soil and plastic, via an isotopic method (<sup>13</sup>C %), which provided more accurate tracing of carbon via <sup>13</sup>CO<sub>2</sub> measurements compared to non-isotopic methods. The reported degradation rate was similar to conventional plastic (HDPE) and significantly lower than

the biodegradable plastics (PBAT-starch) studied, with an estimated mean residence time of 163 years of the recalcitrant carbon pool (i.e., the carbon pool in soil resistant to microbial breakdown). Again, emphasising the very slow degradation of these materials in the environment.

Similar findings of negligible biodegradation have been reported in aquatic/marine environments. A comparative study investigating the degradation of ODPs (Symphony Environmental Ltd., UK; d2w pro-oxidant) under natural weathering in an open-air environment, in pond water, and in distilled water over 48 months reported oxidation and fragmentation of ODPs after 39 months in the open environment, reduction in mechanical properties and minor fragmentation after 48 months in pond water, and negligible degradation after 48 months in distilled water [43]. This highlights the necessity of sufficient oxygen, UV and temperature to drive degradation processes, which are unlikely to be achieved in aquatic environments. Similar findings were made after 6 months, where ODPs (pro-oxidants: EPI, d2w) were in an open-air and marine environment. Here, oxidation and fragmentation of ODPs occurred in the open-air whilst biodegradation in the marine environment was minimal [44].

Work published as part of the OXOMAR project, part-funded by Symphony Environmental Ltd. [45] emphasised the role of photo-thermal pre-oxidation in the degradation of ODPs (Symphony Environmental Ltd., UK; d2w pro-oxidant) [46]. The pre-treatment involved two steps; firstly, 40 hours photo-exposure to wavelengths > 300 nm at 60 °C, which caused photochemical induction and formation of photoproducts (carboxyl acids). Secondly, thermal oxidation at 60 °C for 25, 100 or 300 hours, with samples then being immersed in water (water specifications e.g., purity, pH, are not given). Results showed that oxidation occurred and was highest in samples with longer pre-treatment periods as measured by a suite of analytical techniques. However, without pre-treatment, oxo-degradable polymers behaved comparably to conventional polymers and did not release any measurable degradation compounds into the water [46]. The report also concluded that complete degradation in the marine environment after periods specified in standards (e.g., more than 60% degradation for ISO 18830 [47] and ISO 19679 [48] or 70% for ASTM D6691-09 [49] after 24 months) could not be determined [50]. Subsequently, the role of pre-treatment in the biodegradation of ODPs in marine environments has been further emphasised [51, 52]. Studies comparing the biodegradation rate of ODPs in marine environments with and without oxidative pre-treatment found that whilst pre-treated ODPs showed higher oxidation rates, neither showed significant signs of biodegradation after 60 d (P-Life Japan Inc., Japan) [51] or 12 months exposure in seawater (pro-oxidant: manganese stearate) [52].

The observed fragmentation of pre-treated ODPs and negligible/limited biodegradation indicate that ODPs do not biodegrade in marine environments but may act as a source of MPs. This also **highlights that artificial laboratory degradation is unsuitable for use as a predictive model of degradation in the natural environment due to the complex interactions of environmental factors influencing degradation, and that oxidative degradation of ODPs is largely absent in marine conditions.** The concerns regarding

transferability of artificial degradation results to open environments are supported by another study investigating the additive leaching of ODPs (0.2% w/w manganese stearate) in marine environments after 9 months, with and without prior artificial degradation [53]. They reported a significant difference in additive concentration of the ODPs, which was mainly driven by the oxidative pre-treatment and less influenced by exposure time in the marine environment. This highlights the importance of understanding the interaction between weathering processes and ODP composition, and the need for industry transparency on ODP composition, to inform risk assessments for natural environments.

**In summary, the review of recent evidence supports previous conclusions [8, 9, 10]: Evidence that ODPs follow the same degradation behaviour shown under laboratory testing conditions when exposed in natural environments is lacking. Evidence shows negligible biodegradation in aquatic/marine environments, and underscores that degradation is initiated by photo-thermal exposure prior to immersion in water. Laboratory degradation tests are unsuitable to predict degradation in open environments.**

**Considering the climatic conditions in Wales, whilst acknowledging that abiotic and biotic degradation will occur, this will likely progress at a slow rate as degradation processes are highly influenced by the exposure conditions.**

## *5.2. Degradation of ODPs in managed waste systems*

The conditions of waste management systems (such as landfill, industrial composting, and recycling) vary widely. In addition, regulations regarding the disposal of specific plastic types can vary regionally, leading to uncertainty for consumers and plastic entering an unsuitable waste stream [54]. Waste in landfills is usually compacted and buried under soil, permitting anaerobic degradation only, with no regulation of temperature or moisture content. The resulting methane emissions are captured and utilised for energy generation. The leachates from degrading waste are collected and pass through wastewater treatment plants before entering the open environment [55]. Recycling of plastic in the UK is currently regulated by local authorities, meaning that the suitability of plastic types for recycling can vary regionally. The inclusion of biodegradable and oxo-degradable plastics into existing recycling streams is met with concern due to the potential impact on recyclate quality [56]. A separate collection and recycling systems is proposed for these plastic types [56]. Similarly, the suitability of plastic to enter the industrial composting stream varies regionally and depends on available facilities. Despite plastic products being labelled as compostable, the regional infrastructure plays a significant role in the end-of-life disposal route. Composting

facilities usually operate under aerobic conditions with high temperatures and moisture content, to facilitate biodegradation of materials.

The disposal of ODPs in managed waste systems proves challenging, as their degradation follows a two-step approach: first, oxidation and breakdown of the polymer chain into small low-molecular weight fragments requiring oxygen and elevated temperatures/UV; second, these molecules can then be assimilated by microbes and turned into microbial biomass, water, and CO<sub>2</sub>. However, in landfill the first crucial step of the degradation process is inhibited by the lack of light and oxygen, resulting in negligible degradation rates as the catalysts cannot achieve their intended function, subsequently severely limiting biotic degradation [9, 10, 16]. ODPs should not be composted as they are not compliant under the EN 13432 [57] or ASTM 6400 [58] standards, and risk contaminating composts with persistent residues [9, 16]. Lastly, recycling of ODPs alongside conventional plastic materials is currently not a viable option because the pro-oxidants present in the material mixture negatively affect the structural integrity of the recyclate [9, 10], rendering low quality outputs.

While manufacturers recommend that ODPs are only disposed of in landfill at end-of-life, the absence of clear labelling specifying disposal instructions on the plastic can result in consumer confusion and inappropriate disposal [59].

**Since ODPs have been primarily designed to degrade in open-air conditions – where oxygen availability and UV light promote degradation, end-of-life options such as composting, recycling, and landfill are ambiguous. This complicates the end-of-life management of ODPs and would undermine sustainability efforts aimed at increasing material circularity, reuse, and recycling, as outlined in the Beyond Recycling Report [60] and the Well-being of Future Generations Act 2015 [61].**

### 5.3. *Generation of microplastics*

The chemical degradation of ODPs results in changes to the material properties, e.g., reducing tensile strength, eventually leading to the physical fragmentation of the plastic into smaller fragments and particles (MPs and NPs). The fragmentation into smaller particles increases the relative surface area, allowing for more efficient biotic degradation as microbes have a greater area to colonise. However, as stated in the sections above, there is currently no sufficient evidence to support the assumption of complete biodegradation of ODPs, indicating a high probability of MP and NP formation in terrestrial and aquatic environments [8, 9, 10, 16, 43, 44, 51, 52]. It is also noteworthy that physical fragmentation of plastic is strongly reliant on the input of external mechanical force, and whilst chemical degradation embrittles the material over time, physical fragmentation in the natural environment can take longer than predicted by standardised laboratory tests [5].

The review of recent scientific literature published since 2023, directly aligns with the findings of previous reports [8, 9, 10]. There is high potential for the formation and persistence of fragments (MaPs), MPs, and NPs in the natural environment and managed waste system. Caution should be applied when assessing the degradation of materials in real-world scenarios, as fragmentation into smaller particles does not directly equal biodegradation by microbial assimilation [5].

## 6. Updated evidence review: Environmental impact of ODPs

### 6.1. *In natural environments*

As stated previously, the incorporation of pro-oxidant additives is designed to catalyse oxidation. The degradation process can lead to the release of toxic chemicals and MPs/NPs, and there remains uncertainty about the complete biodegradation of these materials and their long-term environmental persistence and impact [62, 63, 64].

Plastic particles with smaller sizes are more easily transported compared to larger particles, which increases the potential for environmental dispersal not only through watercourses or soil runoff, but also atmospheric transport and deposition [65]. The fragmentation into smaller particles also increases the potential exposure of soil/aquatic organisms and plants, with a subsequent risk of uptake into the food chain [9, 10, 16]. Rather than mitigating the issue of environmental plastic pollution, the propensity for ODPs to fragment offers the potential for widespread transport and exposure, contributing to MP pollution levels [8, 10].

Plastics comprise complex mixtures of chemicals; a recent study evidenced > 16,000 chemicals associated with plastics [63]. There is a lack of transparency around the types and quantities of chemicals used within OPDs, and therefore evaluating their potential to leach from the plastic, their behaviour within natural environments, and their impact remains challenging. In terms of the pro-oxidant metal additives, there is currently an absence of evidence of their bioaccumulation, however this may be reflective of the lack of research on this topic [16]. As with conventional and biodegradable plastics, more research is required to better understand the extent of ODP additive degradation, leaching, and persistence in the environment for a comprehensive assessment of risk [66].

A recent field study investigated the additive concentrations in agricultural soils where mulch films had been applied, and reported high concentrations of organic chemicals (particularly for DBP (dibutyl phthalate)) in soil mulched with ODPs (field sampling; PE-based ODP- no further composition provided) compared to other plastic types (PBAT, PE, PP) [67]. Concentrations of DBP were more than double in soils where ODPs had been used compared to no-mulch film controls. This is particularly striking as all fields with ODP films had < 4 years of continued mulch application, in comparison to conventional plastics application which ranged between 4-30 years. An increase in soil organic chemicals following relatively short periods of agricultural application raises concerns, with further work needed to evaluate the long-term effects on soil and crop health. DBP is a hydrophobic phthalate plasticiser and is recognised as an endocrine disrupting chemical of high concern [68]. Its low water solubility likely contributes to its accumulation in soil. DBP has been shown to have adverse effects on soil microbial communities and plants at low concentrations [67], and studies report reproductive effects in organisms, including the potential for similar effects on humans [68, 69].

ODPs (Polymateria Ltd., UK) showed no adverse effects on earthworms when tested at a concentration of 0.1% (w/w) [40]. Particle size influences bioavailability, i.e., smaller particles are readily available via ingestion to a wide range of organisms as they overlap with the size range of their prey. For ODPs, where generation of microplastics is expected to occur at a similar or faster rate than conventional microplastics, this might increase their risk of uptake in organisms. A laboratory study showed that moth larvae ingested small ODP fragments (PE-based ODP; no further composition provided), which were fragmented further during passage through the digestive tract, leading to excretion of MPs/NPs [70]. The ODPs tested in this study suppressed egg production compared to conventional plastics, suggesting a greater ecotoxicological effect from ODPs.

**In summary, ODPs share many environmental concerns with conventional plastics; however, their propensity to fragment can increase their bioavailability, which along with a lack of transparency of their chemical composition and the potential for these to leach, raises additional concerns. Evidence shows adverse impacts of ODPs on organisms, however there remains a paucity in knowledge regarding their long-term effects, which prevents a comprehensive assessment of their environmental implications [10, 16].**

## 6.2. *In managed waste systems*

As stated in previous sections of this report, there is currently no suitable waste management strategy for ODPs, as the intended degradation benefits they provide will unlikely be achieved in landfill conditions, and can leave persistent residue under composting conditions [40], as well as impair the quality of the output material following the recycling process. **The same concerns about MP accumulation, risks of additive leaching, and subsequent ecotoxicity as stated above apply to managed waste systems.** There may be additional implications for ODP residues contained within compost being introduced to terrestrial environments through compost application.

## 7. Transferability of standardised testing scenarios to real-world environments

The current testing standards for (bio)degradability of plastic (e.g., ASTM D6954, PAS 9017, EN 17033) provide frameworks for laboratory assessments of plastic degradability under controlled, and optimised conditions. These tests provide useful information often across different stages of product testing, for example, they reveal a mechanistic understanding of degradation and changes to the chemical and mechanical properties of materials under optimised conditions. However, as these tests are usually carried out under accelerated conditions in the interest of time, (i.e., creating conditions that are not reflective of natural environmental conditions, particularly for climate zones such as Wales), their transferability to natural environments is not recommended [5, 8, 9, 10, 16, 40, 52, 53].

It is important to note **that testing frameworks listed below (Table 3) are guidance and do not set pass criteria, hence they cannot be considered as specification standards or certification of performance.** It is also important to note the purpose of these tests which is stipulated on the cover document of each test, for example ASTM D6954 states that “the correlation of results from this guide to actual disposal environments (for example, agricultural mulch films, composting, or landfill applications) has not been determined, and as such, the results should be used only for comparative and ranking purposes” [34]. Therefore, **any manufacturer's claims extrapolating from laboratory test conditions to environmental performance are not supported by data generated from the testing framework.**

Data from field trials investigating the degradation of ODPs in natural environments are limited, and results vary greatly depending on the environment in which the study was carried out. As of the time of this report, there is no evidence supporting the biodegradability of ODPs in natural environments similar to Wales [9, 40]. To more comprehensively understand how ODPs behave and degrade in natural environments, replicated multi-year and multi-site studies across a global climate gradient are required.

**The current laboratory testing guidelines do not capture the complexity of environmental factors and should not be used to extrapolate performance under real world scenarios [8, 9, 10, 16].**

**Table 3.** Overview of ASTM testing guidelines and notes regarding the extrapolation of test results to natural environments.

Test number	Test name	Notes included with the test guidelines
ASTM D6954 [34]	Standard Guide for Exposing and Testing Plastics that Degrade in the Environment by a Combination of Oxidation and Biodegradation	<p>Note 5.2 <b>“The correlation of results from this guide to actual disposal environments (for example, agricultural mulch films, composting, or landfill applications) has not been determined,</b> and as such, the results should be used only for comparative and ranking purposes.”</p> <p>Note 5.3 <b>“The results of laboratory exposure cannot be directly extrapolated to estimate absolute rate of deterioration by the environment</b> because the acceleration factor is material dependent and can be significantly different for each material and for different formulations of the same material. However, exposure of a similar material of known outdoor performance, a control, at the same time as the test specimens allows comparison of the durability relative to that of the control under the test conditions.”</p>
ASTM D5208 [71]	Standard Practice for Fluorescent Ultraviolet (UV) Exposure of Photodegradable Plastics	<p>Note 4.1 “Materials made from photodegradable plastics are intended to show relatively rapid deterioration of chemical, physical, and mechanical properties when exposed to light, heat, and water after fulfilling their intended purpose. <b>This practice is intended to induce property changes</b> associated with conditions that might be experienced when the material is discarded as litter, including the effects of sunlight, moisture, and heat. The exposure used in this practice is not intended to simulate the deterioration caused by localized weather phenomena such as atmospheric pollution, biological attack, and saltwater exposure.”</p>
ASTM D5338 [72]	Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials Under Controlled Composting Conditions, Incorporating Thermophilic Temperatures	<p>Note 5.2 “Limitations—Because there is a wide variation in the construction and operation of composting facilities and because regulatory requirements for composting systems vary, this procedure is not intended to simulate the environment of any particular composting system. However, it is expected <b>to resemble the environment of a composting process operated under optimum conditions where thermophilic temperatures are achieved.</b> More specifically, <b>the procedure is intended to create a standard laboratory environment that will permit a rapid and reproducible determination</b> of the aerobic biodegradability under controlled composting conditions.”</p>

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## 8. Conclusion

This review aimed to address the following key points:

1. The degradation of ODPs
  - a. in unmanaged natural environments,
  - b. in managed waste systems,
  - c. and the potential formation of microplastics during the degradation process.
2. The environmental impacts of ODPs in unmanaged natural environments and managed waste systems.
3. The assessment of the transferability of standardised testing of ODPs to real-world contexts.

The findings of recent literature (since 2023) directly align with previous reports' conclusions regarding the degradation and fragmentation of ODPs in natural environments and managed waste systems. Evidence of the complete biodegradation of ODPs in the environment and managed waste systems is lacking. Field studies, particularly in the marine environment, highlight limited biodegradation of ODPs, and that a pre-oxidation period (thermal and photo-oxidation in aerobic conditions) is necessary. The consensus of current literature is that ODPs oxidise more rapidly than conventional plastics, subsequently generating MPs at a faster rate, but fail to initiate the biodegradation process in open environments (terrestrial/aquatic/marine). The inverse correlation of ODP concentration and degradation rate supports the prior conclusions of ODPs' unsuitability to enter landfill or composting facilities. No new evidence refutes the claims of ODPs being unsuitable for recycling. Since ODPs are designed to degrade in open-air conditions (oxygen availability and UV light promote degradation), their degradation in composting, recycling, and landfill systems are ambiguous, which complicates end-of-life options and potentially undermines sustainability efforts aimed at increasing material circularity, reuse, and recycling [60, 61].

The increased generation of MPs, as well as the leaching and potential persistence of chemicals, and specific ODP-related additives are cause for concern, and make ODPs potentially more hazardous to the environment than conventional plastics. However, it needs to be noted that a comprehensive comparison with conventional and biodegradable plastics was outside the scope of this review.

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## 9. Competing Interests Statement

The authors declare that there are no competing interests.

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## 11. Appendix

### 11.1. PRISMA methodology

The search for literature according to the PRISMA [90] method was carried out on 18/09/2025 using three databases: Web of Science, PubMed, and Google Scholar. The search terms were as follows: oxo-degradable OR oxo-biodegradable OR “pro-oxidant containing”. The potential search terms d2w, PAC, pro-oxidant, and ODP were not utilised due to prominent use in other unrelated fields (e.g., medicine, biochemistry, engineering). Searches were limited to the date range of 2023 – 2026, and titles and abstracts were screened for matches.

The search resulted in a total of 59 records, split across the databases as follows (Table A1):

**Table A1.** Number of records per database after initial screening.

Database	Web of Science	Google Scholar	PubMed
Number of Records	26	21	13

From the original 59 records, 21 records were identified as duplicates and removed, resulting in 38 remaining records.

These 38 records were screened for availability: 6 records were excluded due to no availability in English, and 1 record was identified as an author comment to an already included record. This first screening step resulted in 31 records.

The 31 records were subsequently screened for applicability. The title and abstract of each record were read and records that did not fit the topic and/or standard of this report were excluded. A total of 7 records were excluded based on this second screening step: 3 records were identified as non-peer-reviewed conference submissions, and 4 records were identified as unsuitable for the purposes of this report (e.g., due to only mentioning ODPs but no discussion of degradation, environmental implications, or behaviour). This second screening step resulted in 24 records.

Lastly, the remaining 24 records were read in detail and records that did not fit the topic of this report were excluded. A total of 4 records were excluded based on this screening step, resulting in 20 records included in this report.

An overview of the screening steps and number of included and excluded records can be found in Table A2.

**Table A2.** Overview of the number of records from 2023-2026 included in this report based on the PRISMA method.

	<b>Number of records at start</b>	<b>Number of excluded records</b>	<b>Number of included records</b>	<b>Reason for exclusion</b>
Initial search	59	21	38	Removal of duplicate records
1 <sup>st</sup> screening (availability)	38	7	31	No availability in English; comment rather than peer-reviewed publication
2 <sup>nd</sup> screening (applicability – title and abstract)	31	7	24	Not peer-reviewed; unsuitable for topic of this report
3 <sup>rd</sup> screening (applicability – full text)	24	4	20	Unsuitable for topic of this report