REVIEW OF EVIDENCE ON OXO-BIODEGRADABLE PLASTIC PRODUCTS

Dr. Sandhya Devalla
The James Hutton Institute
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This work was commissioned by the Scottish Government to support their commitment to align with or exceed the standards of the Directive (EU) 2019/904 on the reduction of certain plastic products on the environment.

Any Scottish Government policy related queries can be directed to Shaun Taylor at supd@gov.scot.

Contents

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Executive Summary

EU Directive 2019/904 stipulates a ban on Single-Use plastic items as covered in Article 5 of the Directive. The ban also includes all 'oxo-degradable' plastic products due to concerns over their incomplete degradation, (leading to microplastics pollution) and issues related to their recycling and compostability. However, manufacturers of 'oxo-biodegradable' plastics argue that these are different to 'oxo-degradable' plastics and so should not be included in the ban.

This document outlines the findings of an evidence review of what oxo-biodegradable plastics are, are they different to oxo-degradable plastics, their environmental impact, and of the types of oxo-biodegradable products (often used in low-value, single-use bags and stationery items) currently available in the market.

- Evidence gathered from literature shows that **there is no difference between** Oxo-biodegradable and oxo-degradable plastics. Both oxo-degradable and oxo-biodegradable plastics are terminologies that have been used to describe those conventional plastics (e.g., polyethylene) that contain 'Prodegradant' additives which aid in (catalyse) the degradation of the end-of-life plastic products by incorporating oxygen from atmosphere. The most commonly used commercial additives are transition metal salts.

- The main categories of oxo-biodegradable products on the market in Scotland are different types of **low-value single-use bags** and **stationery items**. Information on their market size was not readily available.

- The environmental impact of oxo-biodegradable plastic products is substantially affected by the **rate of degradation** in a specified environment (e.g., open-air, composting, landfill). The rate of degradation is dependent on several factors related to weather, soil and microbial conditions and is not easily predictable based on laboratory testing conditions alone as specified in most degradation testing standards.

- **Complete degradation of oxo-biodegradable plastic products** specific to the Scottish climate conditions (e.g. wet, colder, soil microbial activity) has not been proven so far. Slower rates of degradation are expected in colder Scottish climatic conditions leading to fragments/microplastics pollution.

- Since oxo-biodegradable plastics have been primarily designed to degrade in open-air (where there is oxygen availability), sustainable **end-of-life options** such as composting, recycling, landfill are ambiguous.

Background

EU Directive 2019/904 [1] requires member states to ban those Single-use plastic items as covered in Article 5 of the Directive. The ban also includes all 'oxo-degradable' plastic products. The reason provided in the Directive for inclusion of oxo-degradable plastic is because this type "*does not properly biodegrade and thus contributes to microplastic pollution in the environment, is not compostable, negatively affects the recycling of conventional plastic and fails to deliver a proven environmental benefit*". However, manufacturers of oxo-biodegradable plastics claim that these are different to oxo-degradable plastics as they not only just fragment in the open environment, but also biodegrade; therefore, should not be included in the ban [6].

According to definition in the EU Directive, oxo-degradable plastics (OD) are "*plastic materials that include additives which, through oxidation, lead to the fragmentation of the plastic material into micro-fragments or to chemical-decomposition*". The most common commercial additives are transition metal salts which are added to plastic products in standard production processes. The role of additives is to aid (act as catalysts) in the degradation of plastics products in a specific (disposal) environment. There is, however, some confusion over the terminology used to define such additive-containing plastics. Manufacturers prefer to use the term 'oxo-biodegradable' (OBD) plastics to emphasise the biodegradability of these plastics and argue that they are different to 'oxo degradable' plastics mentioned in the Directive and therefore should not be included in the ban.

The overall goal of the EU SUP Directive is foremost to safeguard environmental and human health. In this context, some of the points raised by the Directive, which would be relevant to the current project, in terms of sustainability of OBD plastics as a solution to plastic waste, are:

- The objective of the Directive is to promote a shift of plastic products from single-use or short-lived applications to a more circular economy approach
- Where products are designed in such a way that the quantity of plastic waste generated is reduced.
- Although microplastics do not fall directly within the scope of the Directive, it states that products which release microplastics should be strictly limited.
- Although the focus of the Directive is marine plastic pollution, it takes note of the fact that plastics and its fragments/microplastics generated in the terrestrial environment are a source of plastics pollution to the marine environment.
- The Directive defines 'biodegradable plastic' as those capable of undergoing not only physical and biological decomposition, but also '*recoverable through composting and anaerobic digestion*'.
- The Directive also helps in achieving United Nation's (UN) Sustainability Development Goal 12 for sustainable consumption and production patterns.

In UK, it is reported that around ~290, 000 tonnes of plastic bags and wrapping are thrown away each year [3]. Recycling rate of plastics in UK is just ~45% with the remaining ending up in landfills or littered [4]. The Scottish Government fully supports EU and UN's vision of

phasing-out Single-use plastics. The Scottish Government has set a target that 70% of all waste is to be recycled/composted/prepared for re-use by 2025 respectively [5], and a new Circular Economy bill is due to be presented to Parliament soon. Targets have also been set for waste going into landfill to be no more than 5% by 2025. The Scottish Government is also supporting the ambitious target that 100% for all plastic packaging is to be recyclable or compostable by 2025, in association with the UK Plastics Pact led by WRAP [2, 5].

This study has focussed only on oxo-biodegradable type of plastics. No comparison has been made with any other plastic types (such as compostable or bio-based plastics).

Project Objectives

To gather evidence for the following objectives set out in the specification document, laid out by Scottish Government's Single-use plastics policy officials to support implementation of Article 5 of EU Directive 2019/904.

Objective 1: *An explanation of how oxo-biodegradable plastic products differ in comparison to oxo-degradable plastic as defined in the EU SUP Directive.*

In this section, we answer the following questions:

Part 1) Is there a difference between OBD plastics and OD plastics? Polymer backbone, types of additives and their roles in degradation will be reviewed, to address the 'conceptual' meaning.

Part 2) To provide defnitions from the EU SUP Directive, European Committee for Standardisation CEN/TR 15351, select publications and manufacturer's definitions.

Part 1: Conceptual meaning

(a) Evidence based on polymer backbone, type of additives, their role in degradation - shows ODs and OBDs are the same type of plastic:

Plastic polymers engineered to degrade faster in a specific disposal environment after their required service life to non-toxic end products are called degradable plastics [7]. Conventional polymers such as polyethylene, polypropylene (which do not degrade easily) can be made to degrade faster by using atmospheric oxygen. Additives that accelerate this process are called 'Prodegradant' or 'Pro-oxidant' additives. The most common commercial Prodegradant additives are transition metal salts. Evidence gathered in this study has shown that when transition metal salts containing additives are added to conventional polymers, **such plastics have been referred to as both OD or OBD plastics, in several academic publications**. They are both made from conventional polymers, usually polyethylene & polypropylene, both use transition metal salts as additives, are designed to degrade in the open environments and involve same degradation mechanisms as evidenced from several journal papers/articles [8,

9, 13, 20, 21, 22, 23]. Use of prodegradants is an old technology [7] that has gained commercial significance more recently.

Salts of transition metals such as iron, cobalt, manganese are added typically at concentrations in 1–5 % range by weight and the plastic blends are then processed using standard production processes (extrusion, casting, injection moulding and blow moulding). Although details of exact constituents used in commercial additives that contain transition metal salts are largely patented/proprietary, some details are provided in comprehensive reviews by Ammala et al. [7] and Abdelmoez et al. [13] on additives containing transition metal salts, their mechanisms of degradation of polyolefins, Standard tests, and toxicities. The main manufactures, an overview of additives used and types of products that use these additives is presented in **Table 1**.

Table 1: Main manufactures of transition metal containing additives and types of products (*taken from Ammala et al. [7], Abdelmoez et al. [13] and manufacturer's websites*)

Manufacturer	Additive Tradename	Weblink	Examples finished Products that use Additives
Symphony Environmental	d2W	https://www.symphonyenvironmental.com/	Bin bags, Food bags, Refuse sacks
EPI	TDPA	https://epi-global.com/	TDPA™ for Single-use plastics, Mulch films
Wells Plastic Limited	Reverte	https://www.reverteplastics.com/	Carrier bags, bin liners, Bread bags, plastic netting, Mulch films
Renatura	Nor-X industries	http://www.nor-x.no/ (https://gb.kompass.com/c/nor-x-industry-as/no061216/)	Not much information was available (contains iron-based proprietary ingredient used for biodegradation of polyolefins
AddiFlex	Add-X Biotech	https://www.add-xbiotech.com/ (https://www.packaging-gateway.com/contractors/materials/add-x-biotech/)	food packaging & food service items, carrier bags & waste disposal bags

Degradation mechanisms for OD/OBD plastic products is reported to occur in two stages. The first stage involves breaking down of the long-chain (carbon and hydrogen containing) polymer to smaller fragments (containing carbon, hydrogen and oxygen) by using oxygen from atmosphere. Although oxygen in stage 1 is most important, temperature (thermal degradation) and UV light (photodegradation) can accelerate this process. The role of transition metals is to act as catalysts in stage 1. The second stage involves microorganisms (bacteria, algae, fungi) which consume these fragments as food source, simultaneously and successively [7]. If degradation is completed in a given environment, the polymer will no longer exist and will be converted to (~>90%) carbon dioxide, water & biomass (as happens in a composting environment).

(b) Further Evidence shows ODs and OBDs are the same type of plastic:

(i) DEFRA (http://sciencesearch.defra.gov.uk/)- Oxo-degradable plastics are made of petroleum-based polymers (usually polyethylene) which contain additives (usually metal salts), that accelerate their degradation when exposed to heat and/or light. The plastics are fairly common in the market, being used in a range of applications including carrier bags, packaging and agricultural films. *Oxo-degradable plastics are often marketed as being 'degradable', 'bio-degradable' or 'oxo-biodegradable'*; implying a reduced environmental impact at the point of disposal compared to plastics without the additive.

(ii) *International journal of molecular sciences*, 2020, *21*(4), 1176 [9] - Microbial *degradation of plastic in aqueous solutions demonstrated by CO_2 evolution and quantification*
This is one of the key papers quoted by manufacturers as evidence of biodegradability [6]. *This paper has referred both OD plastics and OBD plastics as pro-oxidant additive-containing (PAC) plastics* (low density polyethylene).

(iii) *Progress in Polymer Science*, 2011 *36*(8), 1015-1049 [7] – *An overview of degradable and biodegradable polyolefins*
This review paper shows OD and OBD plastics to be the same (referring to both as '*Degradable polyolefin'*). The paper proposes the same two-stage degradation mechanism for either type and provides detailed information on degradation mechanisms, history of prodegradant technology, commercial manufacturers of transition metal additives. ("*Degradable polyolefin systems are typically designed to oxo-degrade undergoing changes in chemical structure as a result of oxidation in air, causing the breakdown of the molecules into small fragments that are then bioassimilated*". Furthermore, the paper mentions that additives such as TDPA™ produce oxo-degradable polyolefinic products (whereas TDPA™ manufactures refer to these plastics as oxo-biodegradable) [12].

(iv) *Standards for bio-based, biodegradable and compostable plastics*
https://www.gov.uk/government/consultations/standards-for-biodegradable-compostable-and-bio-based-plastics-call-for-evidence
In this report, plastics containing prodegradant additives aimed at aiding biodegradation process are referred to as *"oxo-degradable or oxo-biodegradable plastics"*

Part 2: Definitions of OBD plastics

Various definitions for OBD plastics are quoted below from EU SUP Directive, European Committee for Standardisation CEN/TR 15351, academic publications and manufacture websites. Although the CEN/TR 15351 gives separate definitions for OD and OBD plastics, there is no mention or discussion about polymer backbone and type of additives.

For the purposes of this report, both OD and OBD plastics are used to describe those conventional polymers that contain additives ('pro-degradant'- most commonly used are salts of transition metals) resulting in a two-stage degradation mechanism.

1) Definition from EU SUP Directive [1]:

There is no separate definition for OBD plastics. However, in the EU SUP Directive, OD plastics are defined as: "*plastic materials that include additives which, through oxidation, lead to the fragmentation of the plastic material into micro-fragments or to chemical-decomposition*". Point 15 in the Directive further describes oxo-degradable plastic as that type that "*does not properly biodegrade and thus contributes to microplastic pollution in the environment, is not compostable, negatively affects recycling of conventional plastic and fails to deliver a proven environmental benefit*".

2) Definition from European Committee for Standardisation CEN/TR 15351 [11]
(*Plastics. Guide for vocabulary in the field of degradable and biodegradable polymers and plastic items*).
Oxo-degradation definition: "*degradation identified as resulting from oxidative cleavage of macromolecules*".

Oxo-biodegradation definition: "*degradation resulting from oxidative and cell-mediated phenomena, either simultaneously or successively*".

3) Definition from academic publications:
Several papers have used the terms OD and OBD for those plastics that contain transition metal salts (e.g., iron, cobalt, manganese) which catalyse the oxidation of conventional plastics. A few examples are given below:

(i) Polymers for Advanced Technologies 2021; 32:1981-1996 [13]
OBD plastics are "*petroleum-based polymers such as polyethylene incorporated with selected additives (metal salts) that give the final product the degradability feature*".

(ii) *International journal of molecular sciences*, 2020, *21*(4), 1176 - 1189 [9]
"*The PAC (pro-oxidant additive-containing) or oxo-biodegradable plastics are polyolefins blended with additives that stimulate the cleavage of polymer chains under oxidative conditions, a feature expected to lead to improved biodegradability.*"

(iii) *Progress in Polymer Science*, 2011 *36*(8), 1015-1049 [7]
OBDs are "*typically designed to oxo-degrade while undergoing changes in chemical structure as a result of oxidation in air, thus causing the breakdown of the molecules into small fragments that are then bioassimilated*".

4) Manufacturers' definitions:

(iv) https://wellsplastics.com/Products/biodegradables/

"*The term 'Oxo-biodegradable' is a hybridisation of two words, oxidation and biodegradable. It clearly defines a two-step process initiated by the Reverte additive to degrade the polymer chain (break up) and make it available for biodegradability within the environment when a treated item has finished its useful life*".

(v) https://epi-global.com/ufaqs/what-are-oxo-biodegradable-plastics/

"*Oxo-biodegradable plastics are conventional plastics, primarily polyethylene or polypropylene, with a prodegradant masterbatch such as TDPA™ added to promote the breakdown of the plastics through oxo-biodegradation*".

(vi) emf-report-1.pdf (symphonyenvironmental.com)
"*Oxo-biodegradable plastic products are made from ordinary polyethylene or polypropylene. They are made in the same way as normal plastic, but the manufacturer adds a catalyst which accelerates a change in the molecular structure soon after its useful life has expired so that it ceases to be a plastic*".

Conclusion (Objective 1):

Our review of existing evidence shows **there is no difference between OBD and OD plastics**. Both terminologies have been used to describe plastic products made of conventional plastics like polyethylene, with prodegradant/prooxidant additives (typically transition metal salts, ~ 1-5% concentration w/w). The additives help in the fragmentation of the polymer in the first stage of degradation with the incorporation of oxygen, followed by simultaneous or successive biodegradation where microorganisms use the fragments as food. Most manufacturers seem to prefer the use of the term OBD plastics to emphasise the biodegradation process, although these terms have not yet been standardised [38].

Objective2: *What oxo-biodegradable plastic products are on the market in Scotland?*

An online search was carried out to obtain information on typical types of commercial OBD products currently available in Scottish markets. **Table 2** summarises the main product types available. The majority of items are low-value products such as bags-bin bags, nappy sacks, food bags etc (made of polyethylene) and stationery items (made of polypropylene). A more detailed list of OBD products is presented in Annex.

Mulching films, used in agriculture to improve crop yield, has been reported to be a significant potential source of microplastics to the terrestrial environment [47]. Hence it is also important to understand their availability in Scotland. However, there is little information available online on OBD mulching films. Through contacting manufacturers directly, we discovered that it appears that OBD mulching films are only manufactured on demand because of the potential degradation that may result upon storage. **Table 3** shows some of the companies in UK that sell OBD mulching films. Our research indicates that the demand in Scotland for OBD mulching films is small, although a more exhaustive investigation would be required for confirmation.

Table 2: Main types of OBD products available online on market in Scotland

Category	Types of Products	Main Tradenames
Bags (Various)	Bin bags, liners, Nappy Sacks, Dog Poo bags, Carrier bags etc	Ecozone, Beaming Baby, Enov, d2w Bags, Shalimar, TDPA™, Beco
Stationery	Punched Pockets, Popper Wallets, Folders, Envelops	Stewart Superior/SECO, Ampac, Snopake
Netting	Christmas tree netting, Netting sleeve	BioXnet
Health Sector	Overshoes	epi's TDPA
Catering	(Flexy) Glasses	Likely imported from China

Table 3: OBD Mulch films traders

Trader/Manufacturer	Weblink	Some information
Polystar	https://www.polystar.co.uk/polythene-products/horticulture-and-agriculture/mulch-films/	Information from phone call-They discourage OBD mulching films; they are aware of EU ban on OBDs
UK Polythene Packaging Ltd	https://www.ukpolythenepackaging.co.uk/	Information from phone call -market is small; they only manufacture OBDs on demand
Samco System (their distributor in UK-J.O. Straughan & Co Ltd	https://www.samco.ie/clear-mulch-film/	Phoned their distributor in UK-they were aware that they sell biodegradable mulch films but did not know what type!
Vitax – 'biodegradable' mulch mats	https://www.vitax.co.uk/	Phoned them- but no clear answer was obtained whether they are OBD plastic products

Conclusion (Objective 2):

Majority of OBD items being sold are low-value products such as various types of bags-bin bags, nappy sacks, food bags etc made of polyethylene. There is a **large on-line market for stationery items,** largely made of polypropylene (which may be more re-usable compared to low-value single-use bags. There was **little evidence of the use of OBD mulching films,** which are manufactured only on request as they do not have long shelf lives.

Objective 3: *The environmental impact of oxo-biodegradable plastic products*

Objectives 3 & 4 of the specification document have been combined as this study found no difference between OD and OBD plastics containing transition metal additives[1].

OBD plastics degrade (including biodegradation) at a faster rate compared to conventional plastics. According to a recent study published by researchers from Queen Mary University London, biodegradation of OBD Low-Density Polyethylene (LDPE) was found to be 90 times faster than LDPE (without additives) under artificial UV aging conditions [9]. However**, 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 OBD plastic product remains in a given environment, the greater chance of increased environmental impact (such as through the persistence of small fragments/microplastics). It has been reported that, to achieve significant biodegradation in a 'reasonable' time period, the fragments from first stage of degradation should be sufficiently small (<5000 daltons) so that microorganisms can use the fragmented molecules as food [7, 13, 15].

1) End-of-life disposal concerns for Single-use OBD plastic products:

OBD products are designed to degrade in open-air environments [41]. Many OBD products are low value products (single-use bags), often contaminated with biological matter, thus not permitting **re-usability**. Due to this contamination, post-consumer **recyclability** is also not practical or economically viable. Pre-consumer recycling is more feasible. However, there are concerns that presence of OBD additive-containing plastics alongside regular plastics could affect the quality and marketability of the resulting products, such as those requiring long life (e.g., damp-proof membranes) [46]. It has been reported that significant slower rates of degradation are expected in **landfill** due to prevailing anaerobic conditions if buried below the surface [20], even if degradation is initiated in the upper layer and would continue, as manufacturers claim [24]. Inherent heterogeneity of waste in landfills also increases the complexity of the biodegradation process [25]. Additionally, the UK is restricting the amount of waste going to landfill and seeking to adopt a more circular economy approach [5].

[1] This change was agreed with Scottish Government Policy team members at the Presentation given by SD on 09/05/2022.

Regarding **composting** as end-of-life option for OBD waste products, the current industrial composting standard BS 13432 timeframe (6 months; more details below) is not suitable for OBDs. Manufacturers of additives claim OBDs require longer time frames under composting conditions. However, it was found that the rate of degradation was slower in composting conditions compared to soil environment [17] including lack of completeness of degradation when using windrow composting [20].

2) Discussion on current Standards:

Standards BSi 8472:2011 and ASTM D6954-18 to which OBD plastics additive manufacturers claim compliance, are a guidance and not specifications, with no strict timeframes for degradability completion [20]. In 2020, a new specification standard, PAS 9017:2020 was released by British Standards Institution as a specification requirement for biodegradability of polyolefins in an open-air terrestrial environment which is applicable to OBD plastics. Not much information is available yet on the adherence of OBDs to this new standard, to the best of our knowledge. There is also a standard EN 17033:2018 specifically for biodegradable *mulch films,* but no evidence was available on OBD compliance to this standard. A very brief discussion is provided below for some of the relevant standards for soil environments [10]. Although testing to these Standards follow a 3-tier methodology, not all the details are given below (e.g., ecotoxicity part of assessments). For more detailed information, please refer to published Standards.

BSi 8472:2011- *Methods for the assessment for the oxo-biodegradation of plastics and of the phyto-toxicity of the residues in controlled laboratory conditions*

- *Not a specification; only a guidance*
- *Timeframe to reach required biodegradation level (50% minimum) is not defined*
- *Test carried out under laboratory condition*
- *no pass/fail criteria*

ASTM D6954-18- *Standard guide for exposing and testing plastics that degrade in the environment by a combination of oxidation and biodegradation*

- *Not a specification; only a guidance*
- *Tested temperature range: 20 °C – 70 °C (not suitable to Scottish weather conditions)*
- *Molecular weight reduction-<5000Daltons; EAB criteria-<5%*
- *≥ 60% biodegradation to be reached but timeframe to reach this level is not defined*

BS 13432 (ASTM D6400)- P*ackaging – Requirements for packaging recoverable through* ***composting*** *and biodegradation – Test scheme and evaluation criteria for final acceptance of packaging*

- *90% of total theoretical carbon dioxide evolution within 6 months*
- *Disintegration not >10% be >2mm within 12 weeks.*
- *OBD plastics do not pass this composting standard (Manufactures of OBD claim that OBD products are designed to degrade between 2 -3 years depending on product application and environment. There is no evidence yet of complete degradability of OBD products under Scottish environmental conditions*).

PAS 9017:2020- *Plastics-Biodegradation of polyolefins in an open-air terrestrial environment-* ***Specification***

- *Molecular weight reduction-<5000Daltons within 28-day weathering period*
- *≥ 90% degradation to be achieved within 2 years*
- *Standard designed for Biodegradability testing in open-air terrestrial environment*
- *Not much data available as it is a new standard*

EN 17033:2018- *Plastics- Biodegradable mulch films for use in agriculture and horticulture - Requirements and test methods*

- *≥90% biodegradation under aerobic conditions for the plastic (i.e., conversion of organic carbon into CO2) within 2 years*
- *natural topsoil from an agricultural field or forest/standard soil at 20 to 28°C condition*
- *No evidence was found of OBD compliance to this standard*

Standard tests such as those discussed above carried out under controlled conditions are not reflective of real environments [20]. The rate of microbial degradation (stage 2) is highly variable and dependant on the disposal environmental conditions [14, 16]. There is no clear evidence of complete degradability of OBD plastics in Scottish weather conditions.

It is worth noting that manufacturers themselves acknowledge that the rates of degradation depend on the environmental conditions.

- https://www.reverteplastics.com/oxobiodegradibility.php

"Biodegradation can only occur (whether this is for Reverte™ plastics or for grass cuttings) in environments which have warmth, bacterial activity and moisture. This fact is often overlooked when marketing oxo-biodegradable or hydrobiodegradable materials".

- https://epi-global.com/tdpa-oxo-biodegradable/environmental-claims-usa/

"*Under U.S. laws, products with TDPA™ may not be biodegradable or compostable, depending on the conditions of disposal and the specific product*".

3) Lack of evidence on completeness of degradation of OBD plastic products: *This review is not exhaustive but contains an overview of the current knowledge.*

OXOMAR study (*Degradation, Biodegradation and toxicity of Oxo-biodegradable Plastics in the oceans*; 2016-2020) funded by French National Research Agency and Symphony Environmental Technologies showed clearly signs of OBD biodegradability in *marine waters* compared to conventional plastics [30]. Also, there was no evidence of any significant toxicity from OBD leachates including metals, in marine waters, at the concentrations used except for cobalt. However, this study did not make any conclusions on **completeness** of degradation. Also, unlike terrestrial microorganisms, marine microbes have particularly evolved over millions of years to degrade crude oil which has been part of the marine environment [44]. A significant proportion of marine plastics debris however originates from land [45] where OBD products are designed to degrade. Therefore, the above study does not provide sufficient evidence for terrestrial degradation.

A study testing six types of mulching films (2 low density polyethylene films, 2 oxo-biodegradable and 2 biodegradable) conducted in a greenhouse growing lettuce in South-east Spain showed that the degradation time of oxo-biodegradable films was longer than biodegradable films [26]. Gomes et al. [31] tested OBD polyethylene films in simulated soils by the action of microorganisms in accordance with ASTM G160-03 standard, following initial accelerated aging. They concluded that although biodegradation did occur, it proceeded at a 'slow rate'. Moreover, a decrease in the rate of degradation was observed after 60 and 90 days. Based on a review of published literature from 10 years, Abdelmoez et al. [13], concluded that complete biodegradation of pro-degradant additive containing plastics remains a doubt. Other citations that evidenced lack of completeness of degradation of OBDs over different timeframes are [9, 32, 33, 35, 39, 40].

4) Environmental impact risks from incomplete degradation of OBD plastic products

(a) Risks from Fragments and Microplastics: If OBD plastic products do not completely degrade in the environment, release of microplastics was reported to be of concern [42]. Literature on the risks and environmental impacts from microplastics such as ingestion by living organisms and carriers of pollutants is an on-going field of research and is out of scope of the current study. This report focusses only on evidence of risks associated with OBD plastic products due to potential release of fragments/microplastics. Thomas et al. [23] assessed the environmental impacts from the end-of-life OBD plastics. Their study concluded that OBD plastic products are neither suitable for conventional recycling methods nor suitable for composting due to incomplete biodegradation and concern over formation of fragments in the environment. Napper and Thompson [27] found evidence of fragments and microplastics while testing the open-air degradation of OBD, biodegradable, compostable and conventional high density polyethylene bags over a 3-year period. Contamination from microplastics and nanoplastics as a result of fragmentation of OBD and biodegradable plastics in composts was reported by Markowicz and Szymańska-Pulikowska [34]. Recently, Yang et al. [36] tested different types of mulch films including bio-based and OBD, quantified in soil under simulated UV irradiation. Formation of microplastics were confirmed in both plastic types. However, microplastics formed from OBD mulch films were more concentrated over a narrower size range (0.2 μm – 200 μm), a phenomenon attributed to additives which the authors warn, require more critical attention

(b) Risks from longer-term accumulation of transition metals in soils: Due to the low levels of transition metals added to OBD plastics, there are no shorter-term concerns of toxicological impact of metals [18]. In their review of standards for biodegradable plastics, Kjeldsen et al. [14] have reported that although metals used in the additives are naturally occurring and present in small amounts, an accumulation and increase in concentration of some of these metals may be potentially toxic. For example, cobalt at higher concentrations was found to be toxic to microorganisms. Cobalt toxicity was also reported in other studies [30,31]. Al-Salem et al. mentioned that regulating the content of heavy metals is essential for a more sustainable practice [37]. The review article published by DEFRA on OBD plastics highlighted concerns over the potential risk from OBD metal additives accumulating in the environment and **getting into water courses** (of 71 different chemicals found in Britain's rivers, copper

came 1st (highest danger), manganese came 7th, iron came 8th and Nickel 12th in terms of risk, many of these metals are used as OBD additives [38].

(c) Greenhouse gas emissions: Gaffey et al. [28] attributed higher Greenhouse gas emissions per kg of product to fossil-based plastics compared to Bio-based plastics (such as polylactic acid, polyhydroxyalkanoate). Abdelmoez et al. [13] have cited that although plant-based plastics (example, polylactic acid) generate carbon dioxide during their end-of life processes, this carbon dioxide is often balanced by an equal amount during the feedstock plant growth stage, unlike petroleum-based polymers that generate volatile organic compounds as well as carbon dioxide. John et al. have reported that since plastics such as polylactic acid are synthesised from renewable and natural sources, this reduces consumption of fossil energy and subsequently reduction in greenhouse gas emissions [43]. Costa and Donner [29] noted that a shift from fossil-based linear economy to a sustainable, bio-based circular economy requires changes at a broader system level involving different sectors along the supply chain. Higher greenhouse gas emissions attributed to fossil-based plastics especially those designed for single-use has also been mentioned by Kjeldsen et al. [14].

Conclusion (Objectives 3 & 4):

There is no doubt that OBD plastics degrade at a much faster rate compared to conventional plastics. However, **complete degradation of OBD products within a specified timescale under colder weather conditions of Scottish climate has not yet been proven**. The **rate of degradation** which determine their environmental impact, depends on several parameters related to weather, soil and microbial conditions and is not readily predictable. **Current standards of certification** discussed above are therefore not reflective of real environments to prove that fragments/microplastics will not be formed in a specific (disposal) environment especially under Scottish climatic conditions. **End-of-life scenarios** for OBD products are also ambiguous.

References

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Annex

Product type - Bags various	Company	Website
Ecozone Biodegardable Bin Liners 	ecozone	https://www.ecozonedirect.com/
Beaming Baby Nappy Sacks 	Beaming baby	https://beamingbaby.co.uk/
Enov Biodegradable Refuse Sacks 	enov, UK	https://www.enov.co.uk/
d2w Bags various (Carrier, Bin bags/Liners, Refuse sacks, Food/Freezer bags) 	Wikaniko	https://www.wikaniko.com/
Beaming Baby Nappy Sacks 		
Beaming Baby Nappy Sacks	Spirit of Nature	https://www.spiritofnature.co.uk/
Ecozone Biodegardable Bin Liners 	Ethical Superstore	https://www.ethicalsuperstore.com/
Ecozone Biodegardable Bin Liners 	THE UK HIGH STREET	https://www.theukhighstreet.com/
d2w Degradable Multi Purpose Bags 	ManoMano	https://www.manomano.co.uk
Ecozone Biodegardable Bin Liners, Beaming Baby Nappy Sacks	Natural Collection	https://www.naturalcollection.com/
Ecozone Biodegardable Bin Liners	Tree of Life	https://shop.treeoflife.co.uk/
d2w bags-various (refuse sacks, Food/freezer bags, wheelie bin liners, Bin liners, Pedal Bin bags, swing bin liners	Big Green Smile	https://www.biggreensmile.com/
OxoDegradable White carrier, swing bin bags,Pedal bin liners 	The Green Stationery Company	https://www.greenstat.co.uk/
Degradable Black Bin bags 		
Shalimar Premium OXO-Biodegradable Garbage bags 	Navaearth, UK	https://www.navaearth.uk/
TDPA™ Oxo-biodegradable Carrier bags 	ebay	https://www.ebay.co.uk/
d2w Degradable Refuse Sacks & Bin Liners	Essential Housewares Company Ltd	http://www.essentialhousewares.co.uk/
Beco Poo Bags with Handles 	Romy Pets	https://www.romypets.com/
Oxo Biodegradable Dust Sheet 	U-PRO Trade Supplies	https://www.u-pro.co.uk/products/
Oxo-degradable Bubble Roll 	UKPackaging	https://www.ukpackaging.com/

Product type - Netting	Company	Website
BioXnet Oxo-Biodegradable LZ Christmas Tree Netting - 2000m Bale 	True Traders , UK	https://truetraders.co.uk/shop/catalogsearch/result/?q=oxo+biodegradable
BioXnet Oxo-Biodegradable LZ Christmas Tree Netting 400m Sleeve 		
Biodegradable Heavy Duty Pea & Bean Jute Netting 		

Product type - Stationery	Company	Website
Stewart Superior Multi Punched Pockets PP, Flush folders  	Officeneeds	https://www.officeneeds247.co.uk/
SECO 100% Oxo Biod Transluscent Popper Wallet 		
Stewart Superior Multi Punched Pockets PP, Popper Wallets 	Office stationery.co.uk	https://www.officestationery.co.uk/
Ampac envelops 		
Snopake Bio2 Pockets, Bio Polyfile Wallet file 		
S Seco Fiolders Cut Flush 		
Stewart Superior 100% oxo Bio Exp Punched Pockets	Didcot OFFICE SUPPLIES	https://didcotofficesupplies.uk/
Various-**SECO** Popper wallets, **Stewart Superior** Punched Pockets, Popper Wallets, Cut Flush Folders	COS	https://www.countyofficesupplies.co.uk/
Stewart Superior 100% Oxo Biodegradable Punched Pockets, **Stewart Superior** Wallet A4,**Seco** PP folder, **Ampac** Envelops	TANNAS	https://www.tannas.co.uk/
Stewart Superior 100% Oxo Biodegradable Punched Pockets	BUY STATIONERY	https://www.buy-stationery.co.uk/
Stewart Superior 100% Oxo Biodegradable Punched Pockets,**Stewart Superior** 100% Oxo Biodegradable Popper Wallet, **SECO** 100% Oxo Biodegradable PP Popper Wallet, **SECO** Cut Flush PP Folder, **Snopake** PP Punched pockets	theofficesuppliessupermarket.com	https://www.theofficesuppliessupermarket.com/
Stewart Superior 100% Oxo Biodegradable Punched Pockets, **Stewart Superior** 100% Oxo Biodegradable Popper Wallet, **SECO** 100% Oxo Biodegradable PP Popper Wallet, **Ampac** Envelops, **SECO** Cut Flush PP Folder	EAZY OFFICE GROUP	https://www.theeazyofficegroup.co.uk/
Stewart Superior SECO Cut Flush PP Folder, **Stewart Superior** 100% Oxo Biodegradable Punched Pockets, Popper Wallets,**SECO** expandable pockets, **Snopake** PP Punched pockets,	THE UK HIGH STREET	https://www.theukhighstreet.com/
Stewart Superior 100% Oxo Biodegradable Popper Wallet, **SECO** Cut Flush PP Folder, **SECO** 100% Oxo Biodegradable Popper Wallet	DTM Office Supplies	https://www.dtmofficesupplies.co.uk/
Stewart Superior 100% Oxo Biodegradable Popper Wallet, **SECO** Cut Flush PP Folder, **SECO** 100% Oxo Biodegradable Popper Wallet, **Ampac** Envelops	Chariot Office Supplies	https://www.chariot.uk.com/
Stewart Superior 100% Oxo Biodegradable Popper Wallet, **Ampac** Envelops, **SECO** 100% Oxo Biodegradable Popper Wallet	stationery wholesaler Ltd	https://www.stationery.im/

Product type - Stationery	Company	Website
Stewart Superior 100% Oxo Biodegradable Popper Wallet, Punched Pockets, **SECO** 100% Oxo Biodegradable PP Popper Wallet, **SECO** Cut Flush Folder, **Snopake** PP Punched pockets, PP Polyfile Wallet, **Ampac** Envelops, **Rapesco** ECO Ring Binder, **GoSecure** Document Envelopes	South West Office Supplies	https://www.swofficesupplies.co.uk/
Stewart Superior 100% Oxo Biodegradable Popper Wallet, Punched Pockets, Snopake PP Punched pockets		https://cwoffice.co.uk/
Stewart Superior 100% Oxo Biodegradable Popper Wallet, Punched Pockets, **SECO** Cut Flush Folder,	Leo Office Supplies	https://www.leoofficesupplies.co.uk/
Ampac envelops, **Stewart Superior** Eco Biodegradable Wallets, **SECO** 100% Oxo Biodegradable PP Popper Wallet, **SECO** Cut Flush Folder	The Green Office	https://www.thegreenoffice.co.uk/
Stewart Superior 100% Oxo Biodegradable Popper Wallet, Punched Pockets, **SECO** Cut Flush Folder, **Snopake** PP Punched pockets,PP Polyfile Wallet	CW Office	https://cwoffice.2020prosoftware.com/
Stewart Superior 100% Oxo Biodegradable Popper Wallet, Punched Pockets, **SECO** Cut Flush Folder, **Ampac** Envelops, **Sseco** Pocket PP	Office Lines	https://www.officelines.co.uk/
Ampac Envelops	Heatons	https://www.heatons.net/
Ampac Envelops, Stewart Superior Eco Biodegradable Wallets, Popper Wallet, SECO Cut Flush Folder,	Alpha Business Centre	https://www.alpha-business-centre.co.uk/
Stewart Superior 100% Oxo Biodegradable Popper Wallet, Punched Pockets, SECO Cut Flush Folder	EKS	https://www.eks-office.com/
Snopake PP Punched pockets, Bio2 Ring Binder	Ryman	https://www.ryman.co.uk/
Stewart Superior 100% Oxo Bio Exp Punched Pockets, Cut Flush Folders	OnBuy - UK Online Marketplace	https://www.onbuy.com/
Postal mailing bags and Packaging	Poly Postal Packaging	https://www.polypostalpackaging.com/Oxo-biodegradable-additives
Product type - Health Sector	**Company**	**Website**
Overshoes 	Blue Box Socks	https://www.blueboxsocks.co.uk/
Product type - Catering	**Company**	**Website**
Oxo-Biodegradable Flexy Glasses (various sizes) 	Pattersons	https://www.pattersons.co.uk/
Oxo-Biodegradable Flexy Glasses (various sizes) 	Drink Stuff	https://www.drinkstuff.com/products/