EXECUTIVE SUMMARY

BENEFITS AND CHALLENGES
OF BIO- AND OXO-DEGRADABLE PLASTICS

A COMPARATIVE LITERATURE STUDY

STUDY DSL-1

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The unmanaged disposal of plastic waste is a mounting environmental issue. Conventional non-(bio)degradable plastics, when unmanaged, are accumulating in nature, leaving behind an undesirable visual footprint.

It is against this background that (bio)degradable plastics started to appear on the market and can, taken into account their end-of-life options, reduce both visual pollution and accumulation in nature.

Currently, two major groups of (bio)degradable plastics exist. “Biodegradable plastics” cover polymers like polyesters from fossil and renewable raw materials, potentially also in combination with starch and cellulose, polyhydroxyalkanoates and others like PLA which degrade in one or more environments, depending on the conditions. The second group uses non-biodegradable conventional polymers and blends in one or more additives which would make the polymer biodegradable if exposed to oxygen, heat and/or light. These additives can be of inorganic nature (“oxo-degradable”) or of organic nature (“enzyme-mediated degradable”).

The purpose of this study is to evaluate the differences, advantages and disadvantages of “oxo-degradable plastics”, at this moment the most widely spread type of additivated plastics amongst this family, versus “biodegradable plastics” for the purpose of creating a uniform and scientifically correct communication.

For reasons of good readability, the terms “biodegradable plastics” and “oxo-degradable plastics” are being used to represent respectively plastics which are ultimately biodegradable, mineralizing into carbon dioxide, water and new biomass, as defined by the harmonized EU norm EN 13432, and plastics that follow the degradation mechanism of “oxo-degradation”, characterized by oxidative cleavage of macromolecules, as defined by CEN/TR 15351. However, it must be noted that the term “oxo-degradation” is not standardized, only the process is.

The first chapter of the study deals with biodegradable plastics, or plastics for which degradation is caused by biological activity, more in particular enzymatic, microbial and/or fungal activity. The first biodegradable plastics entered the market in the late 80s, and since then, the market share increased relatively fast, although still representing only a tiny share of the total plastic market.

Based on the raw materials used, biodegradable plastics can be divided into 5 different categories: plastics based on starch, cellulose based plastics, biodegradable plastics obtained via chemical synthesis, biodegradable plastics produced by bacteria and biodegradable plastics of petrochemical origin. Each of these categories has their benefits and challenges which are explained more in detail in this study.
The majority of the biodegradable plastics are compostable, a definition which has been laid down in several standards and norms from which in Europe EN 13432 can be considered as the most important norm due to its harmonized and binding character. The counterparts of EN 13432 are ASTM D 6400 and ASTM D 6868 (US), AS 4736 (Australia) and ISO 17088 and ISO 18606 (worldwide).

In order for a plastic to be categorized as compostable, four criteria must be fulfilled:

1. **Chemical characteristics**: The product must contain at least 50% organic matter and may not exceed several heavy metal limits.

2. **Biodegradation**: The products should biodegrade for at least 90% within 6 months under controlled composting conditions. Biodegradation, or mineralization, is defined as the conversion of the organic C to CO₂.

3. **Disintegration**: The product, under the form which enters the market, should, within a timeframe of 12 weeks, fragment sufficiently to visually undetectable components (< 2 mm) under controlled composting conditions.

4. **Ecotoxicity**: The compost obtained at the end of the composting trial, eventually containing undegraded residuals from the product, should not pose any negative effects to the germination and growth of plants (and also earthworms in case of AS 4736).

Following the above, it can be noted that compostability comprises (much) more than just biodegradability. A product that is compostable is always biodegradable, but a product that is biodegradable is not per se compostable.

EN 13432, and its counterparts, are, however, only applicable for industrial composting, leaving an open space with regard to standardization for home compostability and biodegradation in other environments, like soil, fresh water, marine water and anaerobic digestion.

Objective proof of (bio)degradation (and compostability) of biodegradable plastics is available in different forms. The most robust evidence are the many certificates. Certified materials have been tested according to well defined and recognized test methods and fulfil the requirements of internationally accepted standards and norms like EN 13432. Furthermore, both the laboratory, responsible for the testing, as well as the certification bureau, responsible for the review of the test results, need to be accredited and/or independent.

Besides certification, further proof of (bio)degradation of biodegradable plastics can be found in round robin testing and of course the many publically available scientific articles. In general, it can be concluded that all biodegradable plastics biodegrade completely under industrial composting conditions, a smaller group also biodegrades under home composting conditions and in soil and an even smaller group also in fresh and marine water or even under anaerobic conditions.
Conventional plastics enriched with additives are discussed in detail in the second chapter of this study. The majority of these additized plastics are **oxo-degradable plastics**. These conventional plastics are enriched with inorganic metal salts that should cause the plastic to degrade by a process initiated by oxygen and accelerated by light and/or heat. A smaller share however uses organic additives which are claimed to be consumed by the micro-organisms during which these excrete acids and enzymes that should break down the plastic into materials that are easily consumed by microbes. This latter group of additivated plastics is called “enzyme-mediated degradable plastics” and is only discussed briefly in this study as the focus lays on the oxo-degradable plastics.

For many years, the US guideline ASTM D6954 was the only guide available for testing oxo-degradable plastics. However, since 2009, several other guides and standards were developed in Europe and the Middle East: XP T54 980 and AC T51-808 (France), UAE.S 5009 (United Arab Emirates), BS 8472 (UK), SPCR 141 (Sweden) and JS 2004 (Jordan).

The majority of these guides and standards are composed of three so called ‘Tiers’:

1. **Abiotic degradation (Tier 1)**: Using either accelerated or real-time conditions, samples are subjected to a combination of oxygen, heat and/or light to reduce the molecular weight and/or mechanical properties.

2. **Biotic degradation (Tier 2)**: The residues from Tier 1 are retrieved for biodegradation testing using the environment in which the material is intended to end up after disposal (e.g. compost, soil, water, landfill,…). In most cases the amount and rate of CO₂ production, in case of aerobic biodegradation, and additionally CH₄ production, in case of anaerobic biodegradation, is measured.

3. **Ecotoxicity (Tier 3)**: By using a variety of living organisms, including plants, earthworms and aquatic organisms, the effect of the residues from Tier 2 on the growth, survival and/or immobilization of fauna and flora can be determined.

However, a distinction needs to be made between guidelines and standards. Guidelines like ASTM D 6954 and BS 8472 are comparable with test methods and merely prescribe how the different tests need to be performed. Standards however, like UAE.S 5009 and SPCR 141, also contain specific pass or fail criteria and accompanying timescales in which these criteria need to be met. Consequently, it is not possible to claim conformity with guidelines, only with standards.

Since the introduction of the oxo-degradable plastics however, a lot of questions arose on whether these biodegradable variations of the well-known conventional plastics are indeed really biodegradable. On exposure to oxygen, heat and/or light, these polymers are claimed to disintegrate into small fragments, thereby reducing the visual footprint, however, these fragments can accumulate in the environment if biodegradation happens only partially or not at all.
A significant part of this study therefore focusses on the available data on the (bio)degradation of oxo-degradable plastics.

According to the oxo-degradable industry, the most likely disposal routes for oxo-degradable plastics are recycling, soil surface exposure (through littering and the use of mulching films) and landfilling. Water exposure seems to be a possible disposal route as a result of littering.

The Oxo-biodegradable Plastics Association (OPA) furthermore states that oxo-degradable plastics are not marketed for composting. Unlike biodegradable plastics, despite what is sometimes claimed, oxo-degradable plastics are not compostable, as agreed upon by an important share of the industry. Oxo-degradable plastics do not meet the requirements of (industrial and/or home) compostability set out in the different standards, which means that they cannot be used for e.g. compostable food service applications.

However, according to the oxo-degradable industry, the oxo-degradable plastics do biodegrade completely, but not in the foreseen timeframe as set forth in the different standards on (industrial and home) composting. Numerous scientific articles are available on the biodegradation of oxo-degradable plastics, from which two articles showed a significant level of biodegradation (see Table 1).

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Abiotic degradation</th>
<th>Biotic degradation</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Compost</td>
<td>Soil</td>
<td></td>
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<tr>
<td>Jackubowicz et al.</td>
<td>10 days at 65°C</td>
<td>43% after 607 days</td>
<td>91% after 733 days</td>
<td></td>
</tr>
<tr>
<td>Chiellini &amp; Corti</td>
<td>44 days at 55°C</td>
<td>49-63% after 600 days</td>
<td>28% after 430 days</td>
<td></td>
</tr>
</tbody>
</table>

It must however be noted that the above two articles are the only articles with a considerable percentage of biodegradation. All other articles reported no or only a (very) low level of biodegradation. It can therefore be concluded that the rate and level of biodegradation of oxo-degradable plastics is at least questionable and irreproducible.

The oxo-degradable plastics industry however questions the reliability of the internationally recognized test methods for the determination of the biodegradation. More specifically, it is claimed that the CO₂ production is not the correct parameter for the determination of the mineralization level of oxo-degradable products as oxo-degradable plastics biodegrade at a (much) lower rate. Yet, many natural lignin containing materials are also characterized by a slow mineralization rate and have been tested successfully for biodegradation using these internationally recognized test methods. On other words, these test methods do result in reliable data on biodegradation, even on (very) long term.

In addition to the lower CO₂ production rate, oxo-degradable plastics are also claimed to have a lower tendency to get converted to CO₂ (and a higher tendency to get converted into biomass). However, evidence of such a higher degree of bio-assimilation has not yet been generated.
As the conversion of organic carbon to CO₂ is not recognized by the oxo-degradable plastics industry as the optimal test method, many authors used other parameters to quantify the biodegradation, like microbial colonization, biofilm formation and ADP/ATP ratio. Also the change in physical properties and especially the decrease in molecular weight is often used as proof of biodegradation.

Chiellini et al. tested the biodegradation of a thermally treated additivated LDPE and obtained a plateau at 42-48% after 100 days in fresh water for the low molecular weight extracts with a molecular weight of about 1,000 Dalton. The complete material, including the low molecular weight extracts, showed a mean molecular weight of approximately 4,500 - 5,000 Dalton and only reached a biodegradation level of 12% after 100 days. Molecular weight extracts between 7,500 and 10,000 Dalton showed no significant biodegradation. In other words, the molecular weight of a plastic decreases over time when exposed to oxygen, heat and light, but there is no proof that this continues to levels which result in complete biodegradation.

Even if molecular weight would continue to decrease over time, this only happens under very specific conditions. The majority of the authors used temperatures ranging from 55°C to 70°C. In addition, these (very) high temperatures were also maintained for relatively long periods, ranging from 44 days (at 55°C) to 80 days (at 70°C). Time-temperature superposition principles have been established in the last years as a methodology to translate these accelerated conditions to real-life conditions and the most referenced principle is the Arrhenius principle. However, Celina et al. proved that there is no guarantee that the overall behaviour is of an Arrhenius form. Furthermore, it must be noted this principle is based on the assumption that there is a linear correlation between molecular weight and temperature over a wide range of temperature and not only over a smaller partial range, which cannot be guaranteed. Evidence of the decrease of molecular weight of oxo-degradable plastics at ambient temperature is not available.

The third and last chapter deals with certification. An overview of the different certification opportunities for both oxo- and biodegradable plastics are shown in Table 2.

Compostability can be certified by several certification bodies worldwide. Within Europe, the seedling logo from European Bioplastics and the OK Compost logo from the Belgian certification body Vinçotte are the most important certificates and logos. On a business-to-business level they are both equally well known, whereas on a business-to-consumer level each has geographical preferences. There do exist some other (national) certificates and logos in Europe, but these are less dominant.

Certification for home compostability, and certainly for biodegradation in other environments, is less developed. The OK Compost Home logo from Vinçotte, representing home compostability, is today the most dominant logo on a worldwide scale, although similar other certification opportunities exist as well. With regard to biodegradation in other environments, only Vinçotte and the Swedish Technical Research Institute SP have created some certification systems.
BENEFITS AND CHALLENGES OF BIO- AND OXO-DEGRADABLE PLASTICS

Table 2. Overview of the available certification opportunities for biodegradable plastics

<table>
<thead>
<tr>
<th>Environment</th>
<th>Certification body</th>
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<tbody>
<tr>
<td>Industrial compostability</td>
<td>European Bioplastics (Europe)</td>
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<tr>
<td></td>
<td>Vinçotte (Belgium)</td>
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<td></td>
<td>DIN CERTCO (Germany)</td>
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<td></td>
<td>Biodegradable Products Institute (USA)</td>
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<td></td>
<td>Cedar Grove (USA)</td>
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<td></td>
<td>Japanese BioPlastics Association (Japan)</td>
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<td></td>
<td>Australasian BioPlastics Association (Australia &amp; New Zealand)</td>
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<td></td>
<td>Consorzio Italiano Compostatori (Italy)</td>
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<td></td>
<td>SP Technical Research Institute (Sweden)</td>
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<td></td>
<td>Catalonian government (Catalonia, Spain)</td>
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<tr>
<td>Home compostability</td>
<td>Vinçotte (Belgium)</td>
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<td></td>
<td>DIN CERTCO (Germany)</td>
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<tr>
<td></td>
<td>Australasian BioPlastics Association (Australia &amp; New Zealand)</td>
</tr>
<tr>
<td></td>
<td>Organics Recycling Group – Renewable Energy Association (UK)</td>
</tr>
<tr>
<td>Biodegradability in other environments</td>
<td>Vinçotte (Belgium)</td>
</tr>
<tr>
<td></td>
<td>SP Technical Research Institute (Sweden)</td>
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<tr>
<td>Oxo-degradation</td>
<td>Emirates Authority for Standardization and Metrology (UAE)</td>
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<tr>
<td></td>
<td>Oxo-biodegradable Plastics Association (UK)</td>
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<td></td>
<td>SP Technical Research Institute (Sweden)</td>
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<td></td>
<td>Biosystems America (USA)</td>
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<td></td>
<td>Singapore Environment Council (Singapore)</td>
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</tbody>
</table>

Many biodegradable plastics are certified for industrial and/or home compostability, while only a few are certified for biodegradability in soil and/or fresh water. Oxo-degradable plastics are not certified for industrial or home compostability, nor for biodegradability in soil or fresh water.

Nevertheless, several associations and institutes have created certification systems and accompanying logos for oxo-degradable plastics based on the above discussed guidelines and standards. In this context, several oxo-degradable plastics are certified by the Emirates Authority for Standardization and metrology (ESMA) conform UAE.S 5009. In other words, this means that these products were tested by an independent and accredited laboratory and fulfilled the criteria of UAE.S 5009 (molecular weight level of 5,000 Dalton or lower within 4 weeks and a biodegradation value of at least 60% within 6 months). Yet, the most promising results found in literature, i.e. those obtained by Jackubowicz showing 91% biodegradation in soil after 2 years, only reported a molecular weight value of 8,800 and a biodegradation percentage of only 5% after 6 months. Also Chiellini & Corti, who reached biodegradation levels of > 60% in 1.6 years, only reached 4-7% biodegradation within 6 months.
The final conclusion of this study can be summarized as follows:

1. Biodegradable plastics:
   - The majority do meet the requirements of industrial composting standards, while others biodegrade in other environment as well;
   - Solid proof of biodegradation is available through certification by accredited laboratories;
   - Based on raw materials used, 5 categories can be distinguished: starch based, cellulose based, chemically synthesized, produced by bacteria and fossil based;
   - Standards on specifications are well established for industrial composting, but less developed for home composting and biodegradation in other environments.
   - Biodegradation takes place through biological activity, more in particular enzymatic, microbial and/or fungal activity;

2. Oxo-degradable plastics:
   - Oxo-degradable plastics do not meet the requirements of industrial and/or home compostability set out in different standards (Oxo-biodegradable Plastics Association states that they are not marketed for composting);
   - Conventional plastics additivated with transition metal salts;
   - Since 2009 strong increase in number of standards and guides, although no consistency in content and pass levels (if available);
   - (Bio)degradation claimed to be initiated by oxygen (but inhibited by moisture) and accelerated by UV light and/or heat;
   - Very few positive biodegradation results obtained (those could not be repeated under the same conditions, not by the same author, not by other authors);
   - No proof of Arrhenius’ time-temperature superposition principle at wide range of temperature, which makes extrapolation from abiotic degradation at elevated temperature to real-life conditions scientifically incorrect;
   - Alternative methods (carbonyl index, molecular weight, microbial growth, ADP/ATP,...) no proof of complete biodegradation, only proof of biological activity;
   - Not compostable: better term ‘thermo- or photo-fragmentable plastics’?
   - Different certification institutes, but not always independent or transparent.

3. Enzyme-mediated degradable plastics:
   - Very few data available on biodegradation
   - Conventional plastics additivated with organic additives;
   - (Bio)degradation claimed to take place through enzymes excreted by microorganisms during the consumption of the additive;

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