Intertek Expert Services
Intertek House, Cleeve Road,
Leatherhead, Surrey, KT22 7SB,
United Kingdom

Gary Parker
Sustainability Director

Intertek Expert Services

A Life Cycle Assessment of Oxo-biodegradable, Compostable and Conventional Bags

By Chris Edwards and Gary Parker

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Executive Summary

1 Having read the Life Cycle Assessment prepared by Intertek for the UK Environment Agency and published in 2011, Symphony Environmental was concerned that some of the purposes for which oxo-biodegradable plastic is designed had been excluded from the terms of reference, and that the LCA did not therefore fully reflect the environmental benefits of oxo-biodegradable plastic. Symphony therefore requested Intertek to conduct a further Life Cycle Assessment (LCA) study comparing the environmental impacts of conventional HDPE plastic, oxo-biodegradable HDPE plastic, and bio-based compostable plastic, for use as carrier bags and bread bags.

2 Conventional plastic carrier bags and bread bags are widely used in the UK, with carrier bags often given away free of charge by supermarkets. Many of these bags contain a pro-degradant additive such as Symphony's d_2w which causes the bag to degrade abiotically and then biodegrade after its useful life without affecting the functionality of the bag.

3 Bio-based bags are a relatively new product made from agricultural crops or a blend of crop-based and oil-based material.

4 This study considers the cradle-to-grave life cycle of each of the three alternatives. The functional unit is a 19.1 litre bag for carrier bags and an 800 gram capacity bag for bread bags. The same weight, material content, production energy and distribution distances were assumed for conventional and oxo-biodegradable bags, with a 30% higher weight for bio-based bags.

5 An impact assessment was conducted to assess the bags over 11 environmental impact categories including global warming potential (carbon footprint), abiotic resource depletion (use of non-renewable resources such as oil and metals) and litter. The results can be summarised as follows:

- 5.1 The conventional bag and oxo-biodegradable bag were found to be the same in all environmental impact categories (any differences were well under 1%), except in the litter category where the oxo-biodegradable bag was 75% better.
- 5.2 The global warming potential (carbon footprint) of a conventional or oxo-biodegradable carrier bag was found to be 26.9 grams CO2 eq.
- 5.3 The inclusion of 50% recycled content in the conventional and oxo-biodegradable bags would reduce their impact by 19% in terms of global warming but would have a negative impact on 7 of the other environmental impact categories due to increased shipping.
- 5.4 The bio-based bag was the worst option in 10 of the 11 environmental impact categories due to its higher bag weight and thickness, increased energy consumption, greater transportation and higher end of life impacts.

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1 Introduction

6 Symphony Environmental Ltd is a specialist in controlled-life plastic technology. It produces additives which are designed to reduce the environmental impact of plastic products. The d_2w controlled-life plastic technology developed by Symphony controls and reduces the lifespan of plastic products without impairing their performance during their useful life which is decided at manufacture. However, the environmental benefits of d_2w have not as yet been fully presented within any existing Life cycle Assessment study.

7 This report provides a full LCA comparing conventional HDPE, oxo-biodegradable HDPE and bio-based bags. The conventional HDPE carrier bag is widely used, and is often given away free of charge by shops and supermarkets. Many of these HDPE bags contain oxo-biodegradable additives such as d_2w which cause the bag to degrade abiotically and then biodegrade after its useful life without affecting the functionality of the bag. Oxo-biodegradable bags are sometimes referred to as prodegradant bags. Bio-based bags are made from a starch-polyester blend. They are sometimes referred to as biopolymer or bioplastic bags.

8 The report begins by providing a background to LCA and a review of the key issues including the impact of assumptions involving product composition, weight and use, the implications of the inclusion of short term 'biogenic' carbon on the global warming potential of the product and its competitors, and the inclusion of social impacts such as litter. The goal and scope of the study are then outlined based on the findings of this review. A life cycle inventory is then presented outlining the primary and secondary data used to compare the life cycles of a conventional HDPE bag, a HDPE bag containing the d_2w additive and a bio-based bag for use as carrier bags and bread bags.

9 Finally the results of the impact assessment are presented and include results in terms of global warming potential, litter effects and an additional nine CML impact categories. A sensitivity analysis is also included to assess the effect of comparative weight changes, degradation rates and disposal scenarios.

2 Life Cycle Assessment

10 Life Cycle Assessment (LCA) is defined by ISO (International Standards Organization) as the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle". In other words, an LCA identifies the material and energy usage, emissions and waste flows of a product, process or service over its entire life cycle in order for its environmental impacts to be determined.

11 Figure 1 overleaf illustrates the life cycle system concept of natural resources and energy entering the system and product, emissions and waste leaving the system.

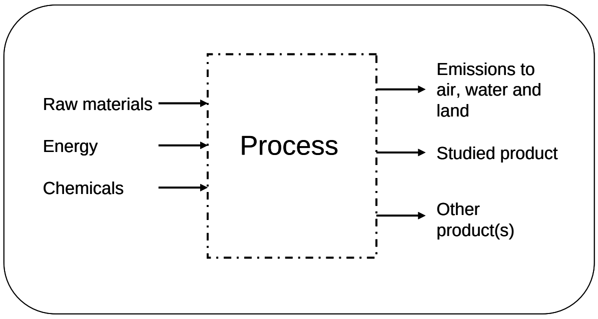

Figure 1, Typical categories of data collected to describe processes in LCA terms

12 Companies undertake an LCA to understand the environmental performance of their product for a variety of reasons including legislative pressures and supply chain issues. Another reason is the increasing number of environmentally conscious customers who are demanding products that combine the benefits of good functionality and low cost with high environmental performance. While an LCA is a valuable tool, it should be emphasised that it is one of many factors, such as cost, consumer acceptance and production feasibility, which companies must take into account during the decision-making process.

13 The technical framework for a life cycle assessment consists of four inter-related stages: goal and scope definition, inventory analysis, impact assessment and interpretation, as shown in Figure 2.

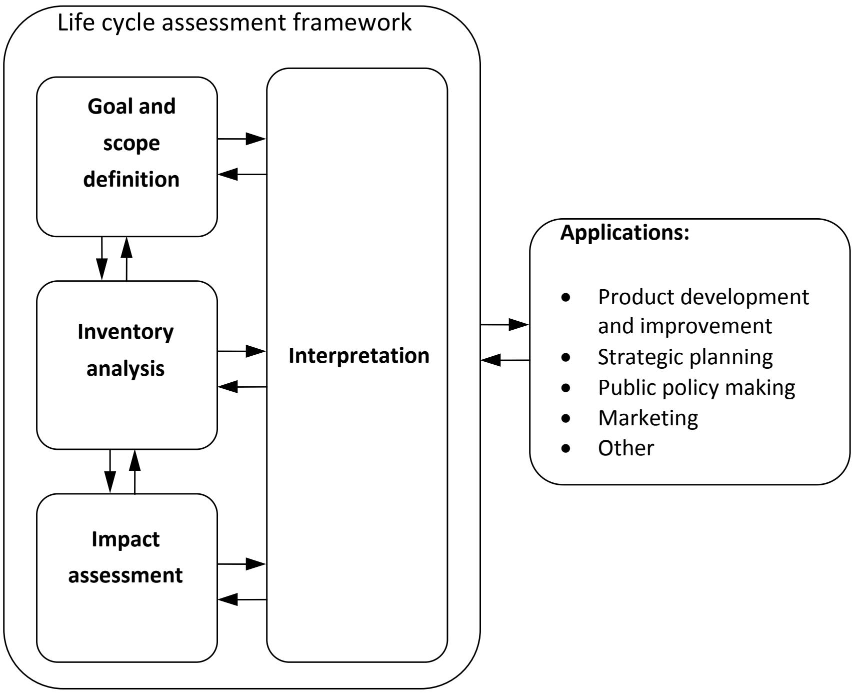

Figure 2, Stages of an LCA (ISO 14040)

14 The ISO standards set out the requirements associated with each stage.

15 The **goal and scope definition** involves identifying the purpose of the study and the systems to be studied, including setting the system boundaries and determining the level of detail included.

16 In the **inventory analysis** all materials, substances and energy used and all emissions and waste released to the environment are identified and quantified over the whole life cycle of the product (from raw material extraction and processing, through manufacture, to use and end of life).

17 The **impact assessment** is a technical, quantitative method used to assess the environmental significance of the inputs and outputs identified in the inventory analysis. The impacts considered can be divided into subject areas such as resource use, human health, and ecological consequences.

18 In the **interpretation** stage, results are analysed, limitations explained, conclusions made and recommendations provided.

19 The following section describes five key life cycle assessments of oxo-biodegradable carrier bags with regards to their goal and scope, the assumptions and data used within their inventory analysis and their impact assessment results.

3 Key Issues

20 A review of existing literature was undertaken to understand the key issues in LCAs of conventional, degradable and bio-based plastic bags. A description of each of the studies that were reviewed is provided in Appendix A. The following sections outline the key issues based on that review and from surrounding literature. These sections are split into three areas: assumptions regarding the extraction, production and use of the production, assumptions regarding end-of-life treatment, and assumptions regarding the inclusion of litter.

3.1 Assumptions regarding the extraction, production and use of the product

21 The review of existing LCA studies comparing the use of oxo-biodegradable additives to conventional and bio-based plastics within lightweight carrier bags found that a significant difference between studies lay in their assumptions regarding extraction, production and use. Although two of the studies (PE Americas 2008 & ExcelPlas Australia et al. 2004) considered the weight, production, distribution and use of the oxo-biodegradable and conventional bags to be the same, the other studies had differing assumptions particularly regarding the weight of the bags.

22 Both Murphy et al (2008) and Varghese et al (2009) assumed a lower weight for the oxo-biodegradable bag when compared to the conventional HDPE bag considered. Conversely, Edwards & Meyhoff Fry (2011) modelled the oxo-biodegradable bag with a higher weight than the conventional bag. However, there is no evidence to suggest that the weight difference is based on any functional difference between oxo-biodegradable and conventional bags. For example, Edwards & Meyhoff Fry (2011) investigated carrier bags provided by all major UK retailers and calculated a weighted average based on market share, bag volume and bag weight. The three supermarkets that used oxo-biodegradable bags were Tesco, Somerfield and the Co-op, taking 45% of the market share and averaging a bag weight of 0.433 grams per litre. However, the other 55% of the market using

conventional HPDE had an average bag weight of 0.425 grams per litre, therefore making the conventional HDPE bag marginally lighter. This was a reflection of UK bag use in 2006 and the weight of the oxo-biodegradable bag was heavily affected by the Tesco bag due to the relatively high weight of that specific bag and Tesco's large market share. The two other oxo-biodegradable bags considered (Somerfield and the Co-op) had a lighter grams-to-litre ratio than any of the conventional HDPE bags considered.

23 The use of an oxo-biodegradable additive had no bearing on bag weight, with the weight difference due to the bag specifications of individual retailers at the time. Similarly, although there were differing material content and production assumptions for the conventional and oxo-biodegradable bags considered, this was based on manufacturer differences rather than any functional difference in bag production.

24 The quantity and material content of the oxo-biodegradable additive also differed between studies. Both ExcelPlas Australia et al (2004) and Varghese et al (2009) assumed the additive content to be 3% while Murphy et al (2008) assumed 4%. The content of the oxo-biodegradable additive was modelled using data on cobalt and stearic acid, although the quantities included varied. Edwards & Meyhoff (2011) correctly identified that the majority of the additive was in fact a conventional HDPE carrier, and therefore only 0.02% was modelled using cobalt/stearic acid data. The influence of the additive on the impacts considered differed when compared to HDPE, although was not found to be significant in any of the studies. PE Americas (2008) and Edwards & Meyhoff (2011) found that the kilogram to kilogram impact of the additive was marginally higher than the impact of HDPE, but the adjusted results of Murphy et al (2008) indicate that the oxo-biodegradable additive had a lower impact than conventional plastic in most categories.

25 Where conventional and oxo-biodegradable bags have been compared to bio-based bags, significant differences exist in the cradle-to-gate assumptions. Most studies considered the bio-based bag to require a higher weight to achieve the same function. The results of most of the studies indicate that the impact of bio-based bag production had a greater influence on impact categories such as eutrophication, acidification land use and water use when compared to conventional polymers.

26 Some studies suggest that the abiotic depletion of resources is lower for bio-based materials due to the lower use of fossil resources during production. This is however questionable because fossil fuels are consumed by machines which clear, plough and harrow the land, spray the crops and harvest them. Fossil resources are also consumed by the machines which make the fertilisers and pesticides, the trucks which bring the seed, the fertilisers and the pesticides to the farm, and carry away the crop. The fertiliser itself is derived from fossil materials. Then when the material is polymerised the factories are also consuming fossil fuels. It is therefore difficult to describe bio-based plastics as "renewable." They may also be in competition with food crops for the use of land and water resources.

27 In the UK and Europe oil-based plastic is made from naphtha, which is an inevitable by-product of the production of petrol, diesel and aviation fuel, which used to be wasted. Oil is

extracted to make these fuels and would continue to be extracted in the same quantity if plastics did not exist. It cannot therefore be said that producing naphtha causes depletion of oil. Oil is depleted only in the process of converting naphtha into polymer. However, following normal LCA convention, all fossil resource depletion is counted in this study, irrespective of whether it truly leads to additional depletion of oil reserves. This means that it could be argued that if a different methodology were to be followed the resource depletion of the oxo-biodegradable and conventional polymers would be lower than stated in this study.

28 Differences occur in terms of global warming potential in several studies (Vaghese et al. 2009, ExcelPlas Australia et al. 2004, Edwards & Meyhoff 2011) finding that the impact of bio-based bags was higher, kilogram for kilogram, than conventional bags while Murphy et al. (2008) found that bio-based bags had a lower impact than conventional bags. This difference was mainly due to the inclusion or exclusion of biogenic carbon dioxide absorbed from the atmosphere during growth, and the assumptions regarding its release at the end of its life. Edwards & Meyhoff (2011) excluded this but found that its inclusion, within a sensitivity analysis, actually increased the GWP of the bio-based bags due to the release of methane in landfill. Methane is a greenhouse gas 23 times more powerful than CO2. It should also be noted that the crops used to make bio-based plastic may not absorb any more CO2 than the vegetation that they have replaced.

29 Murphy et al (2008) included biogenic carbon but assumed that the degradation rate in landfill was low, therefore sequestering and not releasing much of the biogenic carbon dioxide absorbed during growth. This assumption was not supported by evidence. As bio-based plastic does degrade in anaerobic conditions in landfill, producing methane, there is no reason to assume that degradation will not continue until complete.

30 Overall it was found that, if market share and specification are not considered, there is no difference (apart from the inclusion of an oxo-degradant additive) in the material content, weight, production impact and secondary re-use of conventional and oxo-biodegradable bags. This view is supported by Thomas et al (2010) which concluded that the production of *"oxo-degradable polyethylene (PE) bags have the same effect on green-house gas emissions and on depletion of resources as do conventional single-use polyethylene bags"*. Although the same report states that oxo-degradable bags *"are unsuitable for storing items for an extended length of time"* none of the LCA reports considered found a functional difference in the use of oxo-biodegradable bags when compared to conventional HDPE bags. However, in the case of bio-based bags, production differs significantly from that of the HDPE-based bags. This is mostly due to the impacts of plant growth on land and water use and eutrophication, the consumption of fossil fuels in the agricultural and polymerisation processes and the assumptions regarding the absorption and release of biogenic carbon.

3.2 Assumptions regarding end of life treatment

31 All of the studies found that assumptions regarding the end of life treatment of lightweight carrier bags (excluding litter) could have a significant effect on their impact, especially regarding global warming potential (GWP, carbon footprint). The following sections outline the main issues regarding each potential end of life fate: landfill, composting and recycling. Incineration was not included as all studies assume that the inclusion of oxo-biodegradable additive has no effect on the incineration of the plastic and was therefore not seen as a significant issue. The calorific value of oxo-biodegradable and conventional plastics is however greater than that of bio-based plastic.

3.2.1 Landfill

32 Although many of the studies considered several end-of-life scenarios including 100% of each option, those that did consider 'real world' scenarios assumed that the vast majority of bags enter landfill. However, the degradation of oxo-biodegradable and bio-based films in landfill differed significantly from study to study. The most significant impact of this was found on the global warming results of the study conducted by PE Americas (2008). The study assumed that the degradability of the oxo-biodegradable polymer implied that in anaerobic conditions the bag would break down into carbon dioxide, methane and water and that these conditions would exist in landfill. This, the studies suggested, would result in the direct emission of methane from landfill which, despite its partial capture for energy recovery, contributed 47% to the overall GWP. However, the vast majority of existing literature on the subject disagrees with this assumption. Oxo-degradation requires oxygen and cannot proceed in anaerobic conditions.

33 Studies conducted under both aerobic and anaerobic conditions by Mohee et al (2008) found that in the absence of prior oxidation, the amount of carbon dioxide and methane release under these conditions from oxo-biodegradable plastics was similar to those obtained from blank sets, indicating no significant biodegradation. In addition, a landfill study carried out by the University of California (Rojas & Greene 2007) reported that oxo-biodegradable plastic did not undergo anaerobic biodegradation during the study period of 43 days, while a control sample of paper did biodegrade under the same anaerobic conditions to produce methane. Thomas at al (2010) concluded that these findings supported the claims from the producers of oxo-biodegradables that these products will not emit methane in anaerobic conditions in landfill sites. Many of the other LCA studies acknowledge this. For example, Edwards & Meyhoff Fry (2011) considered the landfill of oxo-biodegradable bags to have the same environmental impact as conventional HDPE.

34 The biodegradation of bio-based products in landfill is generally considered to be greater. For example, Murphy et al (2008) assumed that the degradation rate of these bags in landfill conditions occurred but at a low rate of approximately 30% degradation over 100 years. The authors did not of course observe the process for 100 years, and it cannot be assumed without evidence that anaerobic degradation will not continue until 100% complete. A study by the Scottish Executive (2005) reported that a starch-based carrier bag buried under more than 2 metres of waste will result in the emission of methane and carbon dioxide, which has a net impact on its global warming potential even when any benefit of biogenic carbon (absorption of carbon dioxide during plant growth) is included.

Although it is seen as fair to assume that bio-based plastics do degrade to carbon dioxide and methane in landfill, the speed and quantity of degradation is a matter for debate. Murphy et al (2008) reports that recent experiments with starch-polyester in simulated landfill have shown the extent of breakdown of the polymer to be negligible. They state that *"when it is combined with the LCA results they suggest that the 'inadvertent' disposal of [starch polyester] bags (and potentially similar, less readily degraded bio-based bags) in landfills will not generate appreciable quantities of greenhouse gasses and this is in marked contrast with conventional perceptions".* This conclusion is not however supported by other studies and seems unlikely.

35 Although the primary aim of degradable polymers is to degrade quickly after use, the consequences of degradation under anaerobic conditions is significant in terms of global warming potential. It is clear from the findings of existing LCAs and surrounding literature that the anaerobic degradation of oxo-biodegradable polymers is highly unlikely. It is also clear that this degradation can occur in bio-based products.

3.2.2 Composting

36 Jakubowicz et al (2011) report that oxo-biodegradable films mineralise in composting conditions.

37 Thomas et al (2010) did not conduct any experiments but expressed the view that *"oxo-biodegradable plastics should not be included in waste going for composting, because the plastic fragments remaining after the composting process might adversely affect the quality and saleability of the compost"*. However, a commercial-scale composting trial of oxo-biodegradable PE was reported by Billingham (2002) to be successful. The results showed that the oxo-biodegradable plastic was biodegradable under composting conditions, yielding high quality compost with no toxic residues. The final conclusion of this testing was that products containing oxo-biodegradable technology produce compost which is fully acceptable as land fertiliser.

38 Symphony Environmental Ltd has also carried out trials with industrial composters which show that oxo-biodegradable plastic can be processed in an industrial composting process and produce satisfactory compost.

39 Chiellini et al. (2003b) also studied the degradation of LDPE containing oxo-degradant additive and found that it did undergo ultimate biodegradation in simulated soil burial but not as readily in composting conditions because fungal activity in mature compost inhibits microorganisms and therefore reduces the speed of biodegradation.

40 Tests were carried out in Brazil by the laboratory EcoSigma - Soluções Integradas em Gestão de Meio Ambiente Ltda in 2007/08 where it was found that oxo-biodegradable plastic could be satisfactorily composted after abiotic degradation, and that the material contained no heavy metals and was not ecotoxic.

41 There are other reports on the quality of compost containing oxo-biodegradable plastics. ExcelPlas Australia et al (2004) report that *"there is currently little evidence to show that polymer*

residues in the soil are harmful. In fact the contrary appears to be true. Some results suggest that pure polymeric fragments may function like the long-lived components in humus and may provide useful properties as a soil additive".

42 The Nolan ITU Report for the Department of Environment & Heritage of Australia Sept 2003 reports *"The oxidation products of polyolefins are biodegradable*. *Such products have molecular weights that are significantly reduced, and they incorporate polar, oxygen-containing groups such as acid, alcohol and ketone. This is the basis for the term oxo-biodegradable polyolefins. Oxo-biodegradation denotes a two-stage process involving, in sequence, oxidative degradation, which is abiotic, in the first instance followed by the biodegradation of the oxidation-products*."

43 The report continues *"It is evident that oxo-biodegradable plastics based on polyolefins contribute to the amount and nutritive value of the compost because much of the carbon from the plastic is in the form of intermediate oxidation products, humic material and cell biomass. This is in contrast to plastics such as hydro-degradable polyesters that biodegrade at rates comparable to purified cellulose. At the end of the commercial composting process, all of the carbon from the latter has been converted to CO2 so there is a contribution to greenhouse gas levels but not to the value of the compost."*

44 Thomas et al (2010) report that oxo-biodegradable plastics are not compostable according to EN13432; ASTM D6400; Australian 4736 and the comparable ISO standards, but this is due to the timeframe for mineralisation specified in these standards for commercial reasons rather than the inherent compostability of the product. These standards were written before oxo-biodegradable plastic was widely used.

45 For the purposes of this study the main question is whether to include composting as a waste option for oxo-biodegradable plastics. The majority of the LCA studies exclude the composting of oxo-biodegradable bags based on conflicting evidence concerning its compostability and the relevance of the timescale prescribed by existing composting standards. However, composting has been excluded from this study of carrier bags and bread bags because these products are unlikely to find their way into a composting process and will probably be landfilled or become litter. The only plastic products that are likely in practice to be composted in any significant quantity are sacks filled with green waste for industrial composting in a dedicated composting scheme. However, if compostability of all three types of bag were to be included in an LCA, the bio-based compostable plastic would have a high GWP (global warming potential). This is because the industrial composting standards (EN13432; ASTM D6400; Australian 4736 and the comparable ISO standards) require the material to convert substantially into CO2 gas within 180 days.

3.2.3 Recycling

46 It is clear that bio-based compostable plastics cannot be recycled as part of a mixed post-consumer waste stream with conventional and/or oxo-biodegradable plastics and that they would compromise such a recycling stream.

47 Only one of the reviewed LCA studies has assumed that an oxo-biodegradable bag is functionally equivalent to a conventional bag in terms of recycling (PE America 2008). However, oxo-biodegradable plastic can be recycled with other oil-based plastics (a detailed analysis is given in http://www.biodeg.org/position-papers/recycling/?domain=biodeg.org).

48 Recycling does not generally arise in relation to products intended for contact with food or potable water, as recycled content is not normally allowed. Nor is oxo-degradability an issue in relation to low-grade applications such as carrier bags, bread bags, bin-liners or garbage sacks, or in relation to thick cross section products such as garden furniture. Nor is it an issue in relation to long-life products whose standards usually require the use of virgin or stabilised polymer.

49 As oxo-biodegradable plastics are now firmly established around the world, and are even compulsory in the Middle East, it is inevitable that recyclers will have to understand them and process them appropriately. In the UK this is not a significant issue due to the low recycling rate of carrier bags and the use of their recyclate in low-grade applications. Thomas et al. (2010) reported that it was difficult to find evidence of any impact on the recycling stream as *"at present there seems to be very little post-consumer recycling of the sort of plastic film products where oxo-biodegradable plastics are usually used".* One of the peer reviewers of Edwards & Meyhoff Fry commented (page 108) *"Post-consumer shopping bags are printed, and probably often contain some unwanted materials; this would make it very difficult to use shopping bags as a high value plastic."* Moreover, as Edwards & Meyhoff Fry reported, the environmental benefits of re-use outweigh the benefits of recycling.

3.3 Assumptions regarding the inclusion and impact of litter

50 Excelplas Australia et al (2004) used an estimate that, of the 6 billion HDPE bags consumed annually in Australia, 30 million become litter, which equals 0.5% of output (Nolan-ITU et al 2002). Calculations suggest that a rate of 0.75% would be applicable to the UK. These are obviously significant quantities.

51 Although most of the LCA studies have excluded the consideration of litter within the boundaries of the study, two of the studies did attempt to show the benefit of bag degradability on litter and waste. PE Americas (2008) included a post-consumer waste impact category which was defined as 'deposited goods remaining in land for 700 days after the end of the shelf life of the bags'. When the oxo-biodegradable bag was considered in this category, the study estimated 80% mineralisation within that 700 day period, corresponding to the biodegradation observed under laboratory conditions. This is consistent with the 2011 study by Jakubowicz et al.

52 The study conducted by ExcelPlas Australia et al (2004) also considered the impact of litter through a 'litter aesthetics' metric and a litter marine biodiversity metric. However, as the study was streamlined, the values used to calculate the metrics were based on approximate estimates rather than scientific data.

53 The degradation of the oxo-biodegradable bag in the litter stream, and particularly the implications of this degradation on global warming, have also been debated in surrounding literature. Roy et al (2011) report that *“disintegration of the materials into small pieces which may be visible or invisible to the naked eye has been established, but its final entry into the eco-cycle by bio-assimilation or conversion to CO2 and H2O in a realistic time frame is a matter of discussion”.* However, the 2011 study by Jakubowicz et al on oxo-biodegradable plastic according to ISO 17556 found 91% conversion to CO2 within two years in soil. The same study found that biodegradation of the material proceeded more quickly in soil than in compost.

54 A study by Chiellini & Corti (2003) reported conversion of about 50% of the material to carbon dioxide when oxo-biodegradable polyethylene samples were buried in the soil for 550 days.

55 Existing literature suggests that it is possible to show the benefit of oxo-biodegradable polymers on the litter stream, depending on litter rate and degradation rate. It could have negative effects on other impact categories such as global warming potential, but if the normal measurement period of 100 years is considered it is probably realistic to assume that the conventional, the oxo-biodegradable and the bio-based bag will all have aerobically degraded to carbon dioxide during that period.

56 The period required for complete mineralisation (complete biodegradation) of an oxo-biodegradable bag may not however be the relevant period when considering litter effects. The biodegradation phase is preceded by an abiotic process of degradation by oxidation, as indicated above, and at the end of that abiotic phase the material will have fragmented into small pieces which are no longer plastic. The material will no longer have any significant visual effect and will no longer be capable of entangling wildlife or blocking drains. An oxo-biodegradable plastic tested according to ASTM D6954 or BS 8472 will also have been independently tested to ensure that there are no heavy metals and no ecotoxicity. The abiotic phase is much shorter than the period for complete mineralisation and can be as short as a few months depending on the actual conditions in the disposal location.

57 Thomas et al. (2010) reported that there is no evidence that degradable plastics encourage littering, and litter is often accidentally discarded, without any conscious decision.

58 As from 1st January 2012 the environmental authorities in the United Arab Emirates have made it compulsory to use oxo-biodegradable technology for most short-life plastic products.

3.4 Goal and scope

59 The goal and scope of an LCA involves identifying the purpose of the study and information relating to the systems being studied such as the system boundaries (ie what is included/excluded from the study). Based on the findings of the literature review presented in section 3, a number of key assumptions have been made regarding the system boundaries of the study. These assumptions along with the goal and functional unit of the study are presented in the following sections.

3.5 Goal

60 The goal of this study is to evaluate the environmental impacts associated with a conventional HDPE bag, an oxo-biodegradable HDPE bag and a bio-based bag for use as carrier bags and bread bags.

3.6 Scope

3.6.1 Functional unit

61 Any comparison of life cycle impacts must be based on a comparable function (or "functional unit") in order to allow clear interpretation. As the function of each bag is to transport goods, the functional unit should relate to the quantity of good carrier and therefore the volume. Due to this, the functional unit for the study is:

"The production, use and disposal of a single conventional light weight bag and alternatives of the same capacity"

62 This functional unit ensures that if a bag requires additional material or processing to achieve the same function (the ability to carry the same volume/weight of goods) as a conventional bag this will be taken into account. As a carrier bag and bread bag provide different functions, the specific volume or capacity required to fulfil the functional unit differs. These have been identified and are presented in the inventory analysis. All results contained within the life cycle assessment therefore represent the environmental impact generated by the production, use and disposal of this unit.

3.6.2 Product systems and system boundaries

63 The system boundaries define the life cycle stages and unit processes included in the systems to be studied. The study will considered three different formats of light weight carrier bag and bread bag which will include:

- **63.1 Conventional HDPE bag** – A bag predominantly made from High Density Polyethylene (HDPE).
- **63.2 Oxo-biodegradable HDPE bag** – A bag predominantly made from HDPE but also containing the d_2w oxo-biodegradable additive.

- **63.3 Bio-based bag** – A bag predominantly made from starch-polyester.

64 Each of the bag formats will be evaluated in both applications (i.e. carrier bag and bread bag) from 'cradle to grave'. Cradle to grave means that the systems include the extraction of raw material, the production and transportation of input materials and the production of the final product, the products delivery to the customer, its use and its disposal or recovery.

3.6.3 Key Assumptions and exclusions

65 A number of key assumptions and exclusions have been developed based on the review of existing LCA studies conducted in section 3.

66 The assumptions surrounding the 'cradle to gate' life cycle of the product were found to differ in almost every study considered. These key assumptions included material content, production energy and product weight. Although these assumptions were found to be different for the oxo-biodegradable bag when compared to the conventional HDPE bag in some studies, this was due to market conditions and not functional differences. Therefore market conditions have been excluded from this study and consequently the production and distribution of the conventional and oxo-biodegradable bags considers the same bag weight, material content (except for the oxo-biodegradable additive) and production energy.

67 Many previous studies have found that existing bio-based bags are heavier than their conventional alternatives. It has been considered for the purposes of this study that a bio-based bag weighs 30% more than a conventional or oxo-biodegradable bag when providing the same volume and carrying capacity (in reality bio-based bags may need to weigh over 30% more to achieve equivalent strength).

68 The assumptions regarding the disposal of the product were also found to be significant. The majority of studies assumed a 'current' situation for end of life activities that included all options but assumed a significant proportion of bags would be disposed of in landfill. Therefore, a 'current' disposal scenario will be used in this study based on disposal rates to landfill and incineration and the quantity of litter in the UK. In addition specific scenarios for 100% landfill, 100% incineration and 100% litter will be studied within a separate sensitivity analysis.

69 The composting and recycling of oxo-biodegradable bags were excluded from previous LCA studies, as neither recovery process was found to be in significant use for any of the bags considered. However, a recycled-content bag, which is far more significant for an LCA comparison, has been included in a sensitivity analysis. Where recycling is considered, recycled content has been included using the '100-0 or cut-off allocation method' for recycling. This method is the most widely accepted method: recycled content polymer is considered a free input, with the impacts of producing that polymer assigned to its first use, meaning that the only impacts included in this study for recycled content are the impacts of transporting and processing the recyclate. In other words the impact of the collection and recycling process is included within the system boundaries but the recovered material utilised has no environmental impact.

70 Edwards & Meyhoff Fry found that 76% of lightweight plastic bags were re-used, and that 53% of households re-used them as kitchen bin-liners. Other uses were as bin-liners in other rooms, as garbage sacks, and for a variety of other uses. The bags cannot therefore be described as single-use bags. Edwards & Meyhoff Fry stated *"The reuse of conventional HDPE and other lightweight carrier bags for shopping and/or as bin-liners is pivotal to their environmental performance, as reuse as bin liners produce greater benefits than recycling the bags."*

71 Although the re-use of plastic carrier bags as bin-liners and for other purposes has been found to be a significant factor in their impact within previous studies, and differentiates them from paper bags, it was not found to be a differentiating factor between the three types of bag considered in this study. This is because the re-use of each bag has been assumed to avoid the same quantity of bin liners and therefore the same impact. Therefore, bag re-use has been excluded from this comparison. This does not mean the study assumes that this re-use does not occur but it presents a worst case scenario.

72 Assumptions regarding the degradation of the bag in landfill and in the open environment as litter were found to be crucial, especially in terms of global warming potential. Due to the likely anaerobic conditions deep in landfill, it is considered that the degradation of oxo-biodegradable bags does not occur there, and does not therefore create methane nor contribute to global warming. However, the anaerobic conditions would affect bio-based bags, and their degradation and subsequent impact are included in the study. The assumed degradation rate and methodology for landfill and litter are presented in the inventory analysis.

73 Both the oxo-biodegradable and bio-based bags are assumed to aerobically degrade in open conditions when littered, but the degradation and biodegradation rates in the open environment are considered to be quicker for the oxo-biodegradable bag based on the literature reviewed. Bio-based bags will not readily degrade in the open environment unless moist, warm and microbially-active conditions exist – ie very similar to compost.

74 These key assumptions and exclusions, along with other assumptions made, can be summarised as follows:

- 74.1 Conventional HDPE and oxo-biodegradable bags have the same weight, material content (apart from the oxo-degradant additive), production energy and distribution to the consumer.
- 74.2 Bio-based bags weigh 30% more (and are thicker) than conventional and oxo-biodegradable bags with the same capacity.
- 74.3 All bags are produced in China and shipped to the UK.
- 74.4 The bio-based polymer used within the bio-based bag is produced in Italy and shipped to a bag producer in China.
- 74.5 Secondary packaging has been excluded from the study as it has been assumed to be the same for all bag options.
- 74.6 The disposal of each bag is assumed to consist of a 'current' situation which includes landfill, incineration and litter, based on UK statistics.

- 74.7 Recycling and composting have been excluded.
- 74.8 Re-use has been excluded (re-use clearly happens, but is the same for all the bags considered).
- 74.9 The impact of oxo-biodegradable plastics in landfill is the same as that of conventional plastics, with no anaerobic degradation.
- 74.10 Bio-based bags anaerobically degrade in landfill and emit methane.
- 74.11 Bio-based and oxo-biodegradable bags aerobically biodegrade at different rates in the open environment.

3.7 Inventory analysis

75 Inventory analysis is the identification, collection and calculation of inputs and outputs of environmental flows across the system boundaries. The inputs and outputs are scaled to the functional unit and include both elementary and non-elementary flows. Elementary flows are materials or energy entering the system which have been drawn from the environment without previous human transformation, or materials and energy leaving the system which are discarded into the environment without subsequent human transformation.

76 The development of a life cycle inventory depends on the collection of primary and secondary data. Primary data is specific product data and includes material weights and production energy values. Secondary data is data derived from literature and existing life cycle inventory databases.

77 The software tool SimaPro has been used to model the systems and calculate the environmental impacts of the life cycle scenarios studied. SimaPro has been specifically developed by PRé Consultants in the Netherlands for the calculation of life cycle impacts and is one of the world's leading LCA tools.

3.8 Impact assessment

78 The impact assessment phase of an LCA assigns the results of the inventory analysis to different impact categories. The impact categories considered in this study are:

- 78.1 Global Warming Potential (GWP or Carbon Footprint)
- 78.2 Litter effects
- 78.3 Abiotic resource depletion
- 78.4 Acidification
- 78.5 Eutrophication
- 78.6 Ozone layer depletion
- 78.7 Photochemical oxidation
- 78.8 Human toxicity

- 78.9 Fresh water aquatic ecotoxicity
- 78.10 Marine aquatic ecotoxicity
- 78.11 Terrestrial ecotoxicity

79 A description of each of these impact categories is provided in Appendix B. Due to significant differences between the production of conventional plastic bags and bio-based bags in previous studies, especially in regard to global warming, the effects of biogenic carbon absorption and release have been included.

80 For GWP, the IPCC[1] 2007 characterisation factors will be used to translate the greenhouse gas emissions generated by the life cycle scenarios into a single carbon footprint. These characterisation factors will be adapted to included and exclude the absorption of CO2 from the atmosphere and the release of biogenic CO2 emissions.

81 For litter effects, the methodology termed litter aesthetics developed by ExcelPlas Australia et al (2004) has been utilised within the impact assessment.

82 For the remaining nine impact categories, the CML 2 baseline 2000 method, a problem oriented approach developed by the Center for Environmental Science (CML), Leiden University was used. This method addresses the breadth of environmental issues, is internationally recognized and well documented.

83 In addition to the impact assessment, a sensitivity analysis has been conducted to assess the environmental impact of a number of issues:

- 83.1 The effect of 100% landfill, litter and incineration at end of life on global warming potential.
- 83.2 The effect of a 50% recycled content for the conventional and oxo-biodegradable carrier bags.

[1] Intergovernmental Panel on Climate Change

4 Inventory analysis

84 This section outlines the primary and secondary data used to accurately compare the life cycles of a conventional HDPE bag, a HDPE bag containing the d_2w additive and a bio-based bag used as carrier bags and bread bags. The inventory is split into five life cycle stages: material extraction and production, bag production, transport & distribution and end of life. Within each section, the data used to model the life cycle stage of each bag is outlined. A life cycle diagram for each of the bags considered is included in Appendix B.

4.1 Material extraction & production

85 This section outlines the data used to represent the production of each input material within the inventory of each of the bags considered. This includes High Density Polyethylene (HDPE), chalk, d_2w additive and starch-polyester. The quantity of each material required for each bag type is outlined in section 5.2 ('bag production').

High Density Polyethylene (HDPE)

86 The production of HDPE is based on Ecoinvent data on the production of HDPE over 24 different sites in the year 1999. This was originally derived from Plastics Europe data and includes the production, delivery and refining of crude oil, the cracking of ethylene and its polymerisation into polyethylene.

Recycled High Density Polyethylene (rHDPE)

87 The manufacture of recycled HDPE is included within the sensitivity analysis, replacing HDPE to show the benefit of the inclusion of recycled content material. The energy required for recycling is based on internal confidential data and is assumed to take place in China. Recyclable material is also assumed to be collected in the UK and transported to the recycling process in China.

Chalk

88 Ecoinvent data on the production of limestone is used to represent the use of chalk within conventional and oxo-biodegradable bags. The Ecoinvent data represents the production of limestone at one European site during 2001 and includes mining, mineral preparation, calcination, hydration, packaging and loading.

d_2w additive

89 Based on information provided by Symphony Environmental, the content of the d_2w additive bag has been represented by HDPE, manganese and stearic acid. The HDPE content is modelled using the Ecoinvent data outlined above on the production of HDPE. The use of manganese and stearic acid is also modelled using Ecoinvent data.

Starch-polyester

90 Ecoinvent data on the production of modified starch is used to model the extraction and manufacture of the bio-based material used in the bio-based bag. The data was originally derived from an Environmental Product Declaration (EPD) produced by Novamont in 2004. It is representative of production in Italy and includes the use of Italian grid electricity. The quantity of carbon dioxide absorbed from the atmosphere has been adapted to conform to a more recent EPD (Novamont 2010) which states that 1.07kg CO2 is absorbed for every kilogram of starch-polyester produced. (This does not however take account of CO2 absorption by the vegetation already there before the maize crop was planted.)

4.2 Bag production

91 This section presents the quantity of each of the materials outlined in section 5.1, the amount of energy required to transform those materials into a plastic bag and the quantity and destination of any waste produced. Based on data collected by Edwards & Meyhoff Fry (2011) for the UK Environment Agency, the average weight and volume of a conventional or oxo-biodegradable HDPE carrier bag was estimated to be 8.17 grams and 19.1 litres respectively as shown in table 1. The Environment Agency study was based on market conditions during 2006 and therefore identified differences in weight and volume between conventional and oxo-biodegradable bags. However, there is no functional difference between a conventional HDPE bag and an oxo-biodegradable HDPE bag and therefore they have been assumed to have the same weight and capacity in this study: 8.17 grams and 19.1 litres. Similarly, an average 800 gram capacity bread bag was found to weigh 6.47 grams and is also assumed to be the same for both conventional and oxo-biodegradable bread bags.

92 As bio-based carrier bags and bread bags are not widely available in UK supermarkets, the weight of an equivalent 19.1 litre bio-based carrier bag and a 800 grams capacity bread bag is assumed to have a 30% greater weight (i.e. 10.621 grams and 8.411 grams respectively).

Table 1, The average weight and volume of a conventional or oxo-biodegradable carrier bag based on market share (Edwards & Meyhoff Fry 2011).

Supermarket source	Market share	HDPE & HDPE oxo-biodegradable bag weight (grams)	HDPE & HDPE oxo-biodegradable bag volume (litres)
Sainsbury	17.98%	8.83	17.9
Waitrose	4.22%	8.67	20.8
Asda	18.42%	7.48	19.6
Iceland	2.00%	12.62	32.2
Morrisons	12.43%	8.98	21.8
Tesco	33.74%	8.24	17.9
Somerfield	5.99%	5.89	16
Co-op	5.22%	6.48	19.6
Average		***8.17***	***19.1***

93 The materials, energy and waste required to produce each of the 19.1 litre capacity bags are shown in tables 2 to 4. The amount of energy required and waste produced for each bag's production is based on data used by Edwards & Meyhoff Fry (2011). The study estimated that the energy required to produce conventional bags was 0.758kWh of grid electricity per kilogram of bags produced. This was assumed to be the same for oxo-biodegradable bags. For bio-based bags this was estimated to be 1.045kWh of grid electricity per kilogram of bags produced. The wastage rate for conventional bags was found to be 4.81% while the wastage rate for the bio-based bag was found to be 0.57%. The wastage rate for oxo-biodegradable bags was assumed to be the same as conventional bags.

Table 2, The input materials and energy required to produce a conventional HDPE bag with a capacity of 19.1 litres.

Description		Quantity	Unit
Input materials	HDPE	8.154	grams
	Chalk	0.429	grams
Output materials	Conventional HDPE bag	8.170	grams
	Waste (recycled)	0.413	grams
Energy	Grid electricity	0.0062	kWh

Table 3, The input materials and energy required to produce an oxo-biodegradable HDPE bag with a capacity of 19.1 litres.

Description		Quantity	Unit
Input materials	HDPE	8.068	grams
	Chalk	0.429	grams
	d_2w additive	0.086	grams
Output materials	Oxo-biodegradable HDPE bag	8.170	grams
	Waste (recycled)	0.413	grams
Energy	Grid electricity	0.0062	kWh

Table 4, The input materials and energy required to produce a bio-based bag with a capacity of 19.1 litres.

Description		Quantity	Unit
Input materials	Starch-polyester	10.682	grams
Output materials	Bio-based bag	10.621	grams
	Waste (recycled)	0.061	grams
Energy	Grid electricity	0.0111	kWh

94 All of the bags have been assumed to be produced in China and therefore grid electricity use has been modelled using Ecoinvent data on Chinese grid electricity production.

95 The quantity of incoming materials in tables 2 to 4 have been calculated based on the weight of the final bag, the weight of waste produced and the estimated material content of each bag. It has been estimated, based on information provided by Symphony Environmental and the findings of

other studies, that the chalk content of both the conventional and oxo-biodegradable HDPE bags is 5%. The oxo-biodegradable bag is also estimated to have a d_2w additive content of 1%. Most of this additive by volume is conventional HDPE carrier. All other material content of the conventional and oxo-biodegradable HDPE bags is assumed to be HDPE. The bio-based bag is assumed to be entirely produced from starch-polyester. The material content and energy required to produce the bread bags has been assumed to be proportionally the same as the carrier bags.

96 All waste produced has been assumed to be recycled within the same production line at a recovery rate of 90% as estimated by Edwards & Meyhoff Fry (2011). This means that 90% of waste material avoids the production of the equivalent virgin material.

4.3 Transport & distribution

97 The transport and distribution of each bag and their constituent materials is split into two stages: the transportation of the materials to the bag producer in China and the distribution of the final bag to the UK market. The transportation assumptions are heavily based on the assumptions used for the transportation of conventional HDPE bags by Edwards & Meyhoff Fry (2011) and are shown in table 5. The table shows that HDPE, chalk and d_2w additive are assumed to be sourced in Asia. Unlike Edwards & Meyhoff Fry (2011) where the bio-based bag was assumed to be produced in Europe, this study has assumed that bio-based bags are also produced in China. Therefore, the transportation of the starch-polyester bio-based to the production site in China is based on the shipping distance from Italy to China.

98 As the bio-based bag is thicker and heavier than the conventional and oxo-biodegradable bags, the transportation of bio-based bags requires more trucks, consuming more fossil-fuel, emitting more exhaust pollution, and occupying more road space. More warehousing space is also required. Road, rail and sea transport has been modelled using Ecoinvent data. Road transport has been modelled based on the use of a 16-32 tonne EURO 3 lorry, rail transport has been modelled based on average freight rail transport in Europe and sea transport has been modelled based on the use of an average transoceanic freight ship. The transport is by weight, which means that the heavier and thicker bio-based bag requires more trucks, consuming more fossil-fuel, emitting more exhaust pollution, and occupying more road space.

Table 5, The transportation distances for materials to the production site and for each bag to the UK.

Description		Road transport	Rail transport	Sea transport
Input materials	HDPE	100km		500km
	Chalk	200km		500km
	d_2w additive	100km		500km
	Starch-polyester	200km		13,500km
Output materials	All bags	300km	280km	15,000km

4.4 End of life

99 This section outlines the data used to model the end of life phase of each of the bags considered. Based on the scope of the study, there are three end of life options for the bags: landfill, incineration and litter. The quantity of bags released to the open environment as litter was calculated to be 0.75% based on the values outlined in table 6. The figure is derived from statistics from the Marine Conservation Society (2010); WRAP (2011) and Symphony Environmental (2005),. The remaining carrier bags (99.25%) are then split between the conventional disposal routes of landfill and incineration.

Table 6, The calculation of the carrier bag litter rate based on existing statistics.

Ref.	Value	Description
A	2250000	Number of items dropped per day (reported by Symphony Environmental, 2005)
B	821250000	Number of items dropped per year (A x 365 days)
C	7273	Number of plastic bags collected in 2010 survey (Marine Conservation Society 2010)
D	123,543	Number of plastic items collected in 2010 survey (Marine Conservation Society 2010)
E	5.89%	Percentage of plastic litter that is carrier bags (C/D)
F	48347144.31	Estimated number of carrier bags in UK litter (B x E)
G	6446000000	Number of carrier bags given out in 2010 (WRAP 2011)
H	***0.75%***	***Estimated percentage of carrier bags that enter litter (F/G)***

100 The quantity of bags going to each disposal route is based on Edwards & Meyhoff Fry (2011) who estimated that 86% of waste went to Landfill and 14% went to incineration based on UK statistics for household waste. Therefore, the real world scenario for carrier bag disposal was:

- Carrier bags to the litter stream (0.75%)
- Carrier bags to landfill (85.35%)
- Carrier bags to Incineration (13.9%)

101 Each of these scenarios has been studied separately within a sensitivity analysis. The following sections outline the inventory for each of these disposal routes.

Litter

102 As no environmental data currently exists on the impact of waste in the open environment, landfill data was used as a proxy and adjusted based on additional information regarding the degradation of each material in the open environment and its subsequent impact on global warming. Therefore, the release of the conventional and oxo-biodegradable bags to the open environment has been modelled based on Ecoinvent data on the disposal of polyethylene to sanitary landfill. This was adjusted for the oxo-biodegradable bag to account for the impact of biodegradation on global warming. The release of the bio-based bag to the open environment was modelled using Ecoinvent data on the disposal of mixed plastic to sanitary landfill (50%) and data on the disposal of paper to sanitary landfill (50%). This data was also adjusted to account for the impact of biodegradation on global warming.

103 The adjustment of the data to include biodegradation in the open environment was based on the findings of Jakubowicz et al who observed 91% biodegradation of the oxo-biodegradable bag in soil in 24 months.

104 Although a two-year timescale is not representative of the 100 year measurement period normally used for global warming, a degradation rate of 91% has been assumed for the oxo-biodegradable and 50% for the bio-based bags and zero for the conventional bag. Biodegradation was assumed to occur aerobically releasing carbon dioxide to the atmosphere (although in reality some of this would be sequestered in the open environment by the surrounding vegetation). The carbon content of the oxo-biodegradable bag was assumed to be 78.1% based on the carbon content of polyethylene (82.2%) and the polyethylene content of the bag (circa 99.5%). The carbon content of starch-polyester was assumed to be 50% based on the figure for Mater-Bi reported by Razza et al. (2011). However, Mater-Bi is not wholly derived from bio sources and includes fossil raw materials. Therefore the biogenic carbon content of the material does not wholly account for the total carbon content.

105 To understand the social impact of carrier bag litter and the advantages of degradation, an additional impact category was included. The methodology for ‘litter effects’ multiplies the area of littered bags by the time taken for them to degrade. For this study the area of each bag has been assumed to be the same at 0.105m2 (35cm X 30cm).

106 The oxo-biodegradable bag has been considered to degrade abiotically within a six month period in the open environment, the bio-based bag to degrade by hydrolysis within a year, and the conventional bag to degrade abiotically over many decades.

Landfill

107 The disposal of conventional and oxo-biodegradable bags to landfill has been modelled based on Ecoinvent data on the disposal of polyethylene to sanitary landfill. No degradation of the oxo-biodegradable bag was assumed to take place as it does not degrade in anaerobic conditions such as are found deep in landfill. The disposal of the bio-based bag to landfill has been modelled using Ecoinvent data on the disposal of mixed plastic to sanitary landfill (50%) and data on the disposal of paper to sanitary landfill (50%). This data has been adjusted to account for the impact of the biodegradation of the bag in landfill.

108 The adjustment of the bio-based landfill data to include degradation was based on the assumptions of Murphy et al. (2008) and the methodology used by Smith et al. (2001). Murphy et al. assumed that the degradation rate for bio-based material in landfill was 30%. Based on the assumed carbon content of starch-polyester (50%) reported by Razza et al. (2011) this would provide a total dissimilable organic carbon content of 15%, which is comparable with other biomass products such as paper (12%) estimated by Smith et al. (2001). Degradation in landfill is assumed to be 100% anaerobic by Smith et al. and therefore the dissimilable organic carbon content of starch-polyester has been assumed to be emitted as 50% carbon dioxide and 50% methane.

109 Smith et al. (2001) also report that 90% of UK landfill sites include gas control with a methane collection efficiency of 70% meaning that 63% of emitted methane is captured and transformed to carbon dioxide. In addition 60% of this methane is utilised for energy generation at a rate of 4.176kWh per kilogram of methane (Smith et al. 2001), though this may not of course be the case elsewhere in the world. The avoided electricity has been included based on Ecoinvent data on the generation of grid electricity in the UK.

Incineration

110 The disposal of conventional and oxo-biodegradable bags to incineration has been modelled based on Ecoinvent data on the disposal of polyethylene to incineration. The disposal of the bio-based bag to incineration has been modelled using Ecoinvent data on the disposal of mixed plastic to incineration (50%) and data on the disposal of paper to incineration (50%). The benefits of energy generation from incineration have also been added based on information provided by Ecoinvent. The incineration of the oxo-biodegradable and conventional bags was assumed to generate 5MJ of electricity and10.02MJ of heat per kilogram of material incinerated while the incineration of the bio-based bag was assumed to generate 2.4MJ of electricity and 4.9MJ of heat per kilogram of material incinerated based on a 50/50 split between mixed plastics and paper. The avoided electricity has been included based on Ecoinvent data on the generation of grid electricity in the UK while the avoided heat has been included based on Ecoinvent data on the generation of heat from natural gas.

5 Impact assessment

111 The following sections outline the results of impact assessment comparing the conventional HDPE bag with the oxo-biodegradable HDPE bag and the bio-based bag for use as carrier bags and bread bags. The first section provides an overview of the IPCC global warming potential results, the litter effects results and the additional nine CML impact category results. The second section (6.2) outlines the sensitivity analysis conducted on these bags including the affect of comparative weight changes, degradation rates, recycled content and disposal scenarios.

5.1 A comparison of conventional, oxo-biodegradable and bio-based bags

112 The overall results of the comparison of the conventional HDPE bag, oxo-biodegradable HDPE bag and bio-based bag are shown in figures 3 to 5. The results are representative of the impact generated to achieve the function of a single carrier bag with a capacity of 19.1 litres. The results are shown in terms of a percentage to allow all impact categories to be shown together. The chart represents the relative impact of each of the options. The worst option in each category is shown as 100%. Each impact is also split by life cycle stage to show the relative contribution of each stage on the bags' total impact. The actual results obtained for each impact category are shown in table 7. The units range from milligrams (mg) to kilograms (kg). However, the size of the unit is not an indication of the comparative importance of the impact category (meaning that different impact categories should not be directly compared to each other).

Table 7, The Impact assessment results for the conventional, oxo-biodegradable and bio-based carrier bags.

Impact category	Unit	Conventional HDPE carrier bag	Oxo-biodegradable HDPE	Bio-based carrier bag
Global warming potential	g CO2 eq	26.8841	26.9140	39.0341
Litter effects	m2.a	0.0016	0.0004	0.0004
Abiotic depletion	g Sb eq	0.3033	0.3050	0.3527
Acidification	g SO2 eq	0.1533	0.1533	0.3057
Eutrophication	g PO4--- eq	0.0100	0.0100	0.0515
Ozone layer depletion	mg CFC-11 eq	0.0002	0.0002	0.0028
Human toxicity	g 1,4-DB eq	2.1621	2.1623	7.8539
Fresh water aquatic ecotoxicity.	g 1,4-DB eq	0.1589	0.1589	0.9551
Marine aquatic ecotoxicity	kg 1,4-DB eq	0.4122	0.4123	1.6976
Terrestrial ecotoxicity	g 1,4-DB eq	0.0215	0.0216	0.1573
Photochemical oxidation	g C2H4	0.0086	0.0086	0.0134

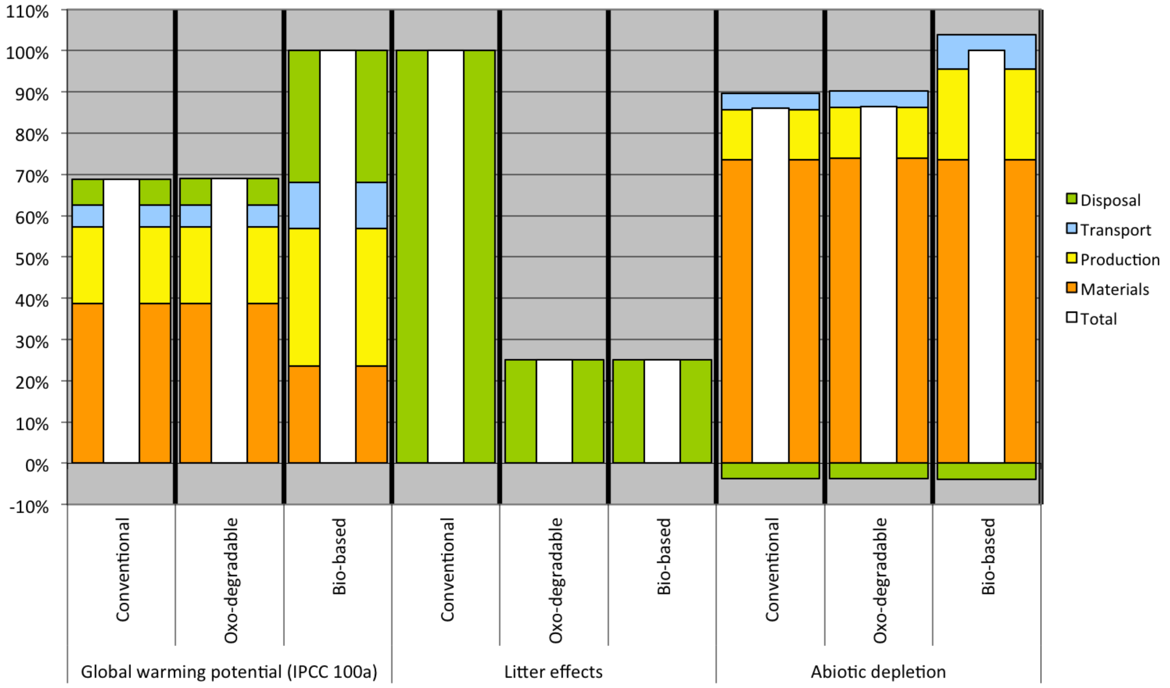

Figure 3, A comparison of the global warming potential, litter effects and abiotic depletion results for the conventional, oxo-biodegradable and bio-based bags.

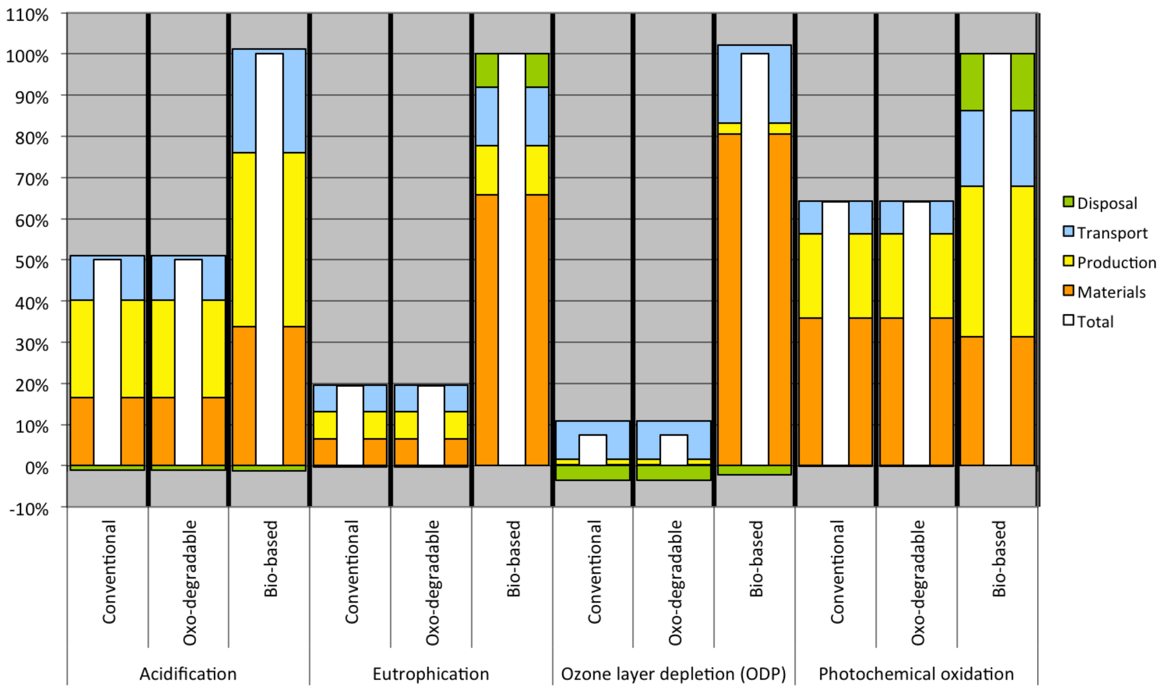

Figure 4, A comparison of the acidification, eutrophication, ozone depletion and photochemical oxidation results for the conventional, oxo-biodegradable and bio-based bags.

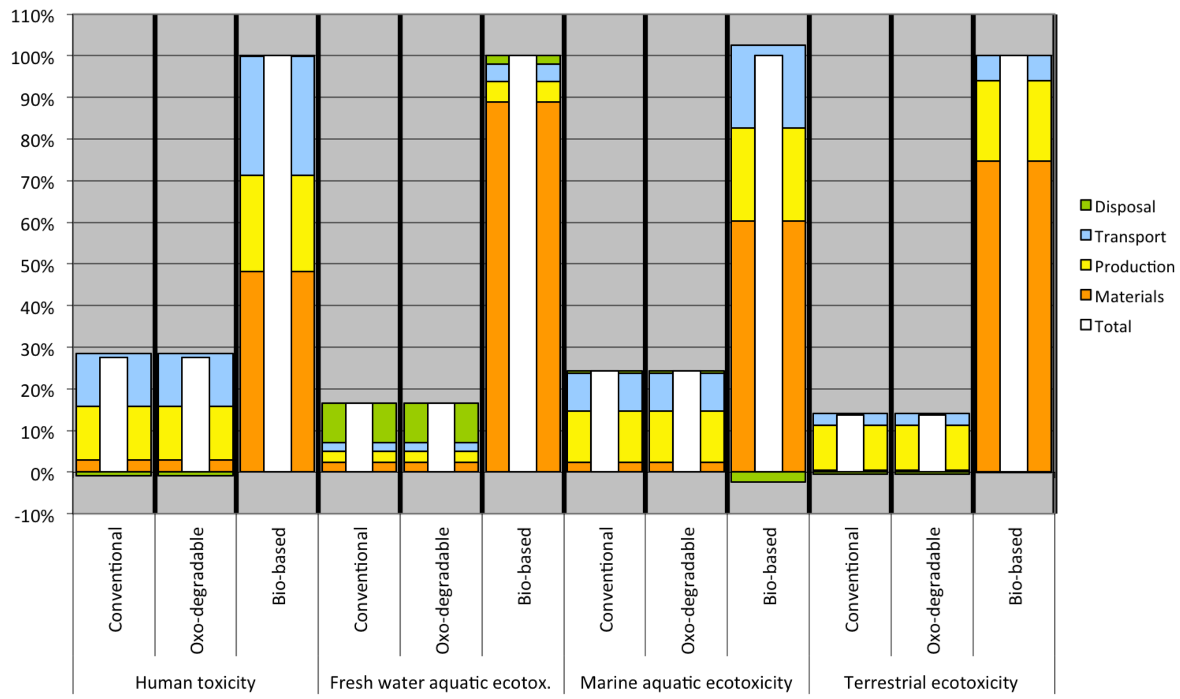

Figure 5, A comparison of the human toxicity, fresh water ecotoxicity, marine ecotoxicity and terrestrial ecotoxicity results for the conventional, oxo-biodegradable and bio-based bags.

113 Similarly, the results for the bread bag are shown in table 8 and represent the function of an 800 gram capacity bread bag. As the material content (except for recycled content) and disposal method of the bread bags is the same as the carrier bags presented in figures 3 to 5, these figures are also representative of the bread bag results.

Table 8, The Impact assessment results for the conventional, oxo-biodegradable and bio-based bread bags.

Impact category	Unit	Conventional HDPE bread bag	Oxo-biodegradable HDPE bread bag	Bio-based bread bag
Global warming potential	g CO2 eq	21.2901	21.3137	30.9120
Litter effects	m2.a	0.001	0.000	0.0003
Abiotic depletion	g Sb eq	0.240	0.241	0.2793
Acidification	g SO2 eq	0.121	0.121	0.2421
Eutrophication	g PO4 eq	0.007	0.007	0.0408
Ozone layer depletion	mg CFC-11	0.000	0.000	0.0022
Human toxicity	g 1,4-DB eq	1.712	1.712	6.2196
Fresh water aquatic ecotoxicity	g 1,4-DB eq	0.125	0.125	0.7564
Marine aquatic ecotoxicity	kg 1,4-DB eq	0.326	0.326	1.3444
Terrestrial ecotoxicity	g 1,4-DB eq	0.017	0.017	0.1246
Photochemical oxidation	g C2H4	0.006	0.006	0.0106

114 Overall, the results can be summarised as follows:

- 114.1 The conventional and oxo-biodegradable bags were found to have the lowest impact in 9 of the 11 impact categories (the difference between these two bags was much less than 1% which means they were effectively the same).
- 114.2 The oxo-biodegradable bags were significantly superior to the conventional and bio-based bags in terms of litter effects, and the oxo-biodegradable bag was also marginally superior (0.01%) in terms of photochemical oxidation.
- 114.3 The bio-based bag was the worst option in 10 of the 11 impact categories and was only found to be superior to the conventional bag in terms of litter effects.

115 The following sections provide a brief overview of the comparison in each impact category and identify where and why differences occurred in the results for each bag.

5.1.1 ***Global warming potential***

116 The global warming potential of the conventional bag was found to be 31% lower than the bio-based bag and only 0.1% lower than the oxo-biodegradable bag. The larger impact of the bio-based bag was due to a number of factors. The transportation and production energy required to produce the 19.1 litre bio-based bag was larger than either of the other alternatives due to the large transportation distance required to transport the starch-polyester from Italy to China and the additional energy required to produce and polymerise the crop and to make the heavier and thicker bag. This resulted in a 79% greater impact from production and a 110% greater impact from transport in comparison to the other options.

117 The bio-based bag also suffers from a significant disposal impact mostly due to the release of carbon dioxide and methane during degradation in landfill. However, there is a level of uncertainty surrounding the GWP of the bio-based bag which will be investigated in section 5.1. The bio-based bag does benefit from a 39% lower impact from materials due to the absorption of biogenic carbon dioxide during plant growth, although this does not take account of absorption by vegetation which was already there.

118 The differences between the conventional and oxo-biodegradable bags are marginal due to the high level of similarity between the bags material content, production, transportation and disposal. The transportation and production impacts of the two bags are identical.

5.1.2 **Litter effects**

119 The assessment of litter effects found that the conventional bag had several times the impact of the oxo-biodegradable and bio-based bags. This was entirely due to the assumption that the conventional bag will take many years to abiotically degrade while the oxo-biodegradable bags will do so within 6 months. The bio-based bag will degrade within 6 months during industrial composting but will take much longer in the open environment. All other assumptions including the quantity of bags going to litter and the area of each bag were identical. Although there is uncertainty

surrounding the actual degradation time for each bag, it is clear that the oxo-biodegradable and bio-based bags have a significant advantage in terms of degradation and therefore this measure provides a fair reflection of that advantage.

5.1.3 Abiotic depletion

120 The abiotic depletion of the carrier bags was found to be one of the closest results in the impact assessment, with the bio-based bag having a 16.3% greater impact than the conventional bag and a 15.6% greater impact when compared to the oxo-biodegradable bag.

121 The most significant influence on this impact category was found to be material extraction and production with this life cycle stage contributing 85.5% to both the conventional and oxo-biodegradable bags (but see 27 above), and 73.6% to the bio-based bag.

122 The disposal stage for all of the bags was found to give a net benefit to this category. This was because the avoided impacts of energy generation through incineration (and landfill in the case of the bio-based bag) outweighed the impacts of disposal. This benefit was marginally greater for the bio-based bag due to the recovery of methane for electricity generation if anaerobically degrading in a suitably equipped landfill site.

5.1.4 *Acidification*

123 The acidification impact category results found that the bio-based bag had a 99% greater impact than both the conventional and oxo-biodegradable bags (which differed by just 0.001%).

124 The significant impact on this category was the use of electricity during production. The greater use of electricity during the bio-based bag's production played an important part in its poor performance. The impact of electricity use on acidification was almost entirely due to the release of sulphur dioxide during the burning of substances such as coal, heavy fuel oil and lignite. The impact of material production was also more than double that of the conventional and oxo-biodegradable bags. This was due to a variety of reasons including the increased weight of material required for the bio-based bag and the burning of hard coal during the production of starch-polyester.

5.1.5 *Eutrophication*

125 The impact of both the conventional and oxo-biodegradable bags in terms of eutrophication was found to be more than 80% lower than the bio-based bag. This was mainly due to the significantly greater impact of the bio-based bag's material production, which was more than 3 times greater. This was because of the release of nitrates to water and ammonia to air during the cultivation of the maize used to produce the bio-based. This ensured that the production of the maize alone contributed more than 51% of the life cycle impact of the bio-based bag. The end of life impacts were also much greater for the bio-based bag due to the release of nitrate and ammonia to water during landfill.

126 The life cycle impacts of the oxo-biodegradable and conventional bags were again almost identical to each other, with just a 0.06% difference.

5.1.6 Ozone layer depletion

127 Ozone layer depletion is not a significant issue, with no bag producing any significant quantities of ozone-depleting substances. However figures are given in this study because of a tiny ozone layer impact arising from shipping.

128 The largest difference between the bio-based bag and the oxo-biodegradable and conventional bags occurred in terms of ozone depletion with the bio-based bag having a 13.5 times greater impact on this category than the other alternatives. This was again due to the production of the bio-based material itself and primarily the shipping of natural gas and heavy fuel oil used during agricultural production and during the conversion of starch into bio-based plastic. Conversely, the impact of the materials used in the conventional and oxo-biodegradable bags was very low, only contributing 2.7% to their impact on ozone depletion. The disposal stage has a net benefit on ozone depletion because the generation of avoided electricity and particularly heat from natural gas during incineration outweighs the other impacts of disposal.

5.1.7 Photochemical oxidation

129 The results for photochemical oxidation found that the bio-based bag had a 56% greater impact on this category when compared to the conventional and oxo-biodegradable bags. The difference between the oxo-biodegradable bag and the conventional bag was negligible at just 0.008%. In this category, as in the litter effects category, the impact of the oxo-biodegradable bag was lower than that of the conventional bag. This was due to marginal differences in the end of life impacts of the bags.

130 Although the bio-based bag had a smaller impact from material production despite requiring a heavier and thicker bag, the impacts of bag production, transport and disposal were all significantly larger than the conventional and oxo-biodegradable bags. The increased production impact was due to the larger consumption of electricity, while the transportation impact was due to the release of sulphur dioxide during shipping. The 14% impact from disposal was due to the release of methane during degradation in landfill.

5.1.8 Human Toxicity

131 Both the conventional and oxo-biodegradable bags were found to have a 72% lower impact on human toxicity when compared to the bio-based bag. This was again mainly due to the production of the bio-based material as well as a larger impact from production and transportation. The impact of material production was due to a number of factors including the release of hydrocarbon and chromium to soil and air during maize cultivation and the release of substances such as chromium and arsenic during the burning of coal and heavy fuel oil during starch-polyester production. The greater impact from transportation was due to the larger transport distances involved for the bio-based bag and the resultant hydrocarbon releases from that additional transportation. The life cycles of the conventional and oxo-biodegradable bags were dominated by production and transport impacts. The production impact was due to the impact of Chinese grid electricity whilst the transport impact was due to emissions from shipping as outlined above.

5.1.9 Fresh water aquatic ecotoxicity

132 The material production life cycle stage of the bio-based bag dominated its impact in terms of fresh water aquatic ecotoxicity, contributing 89% to its total impact, making it more than 6 times worse than the other alternatives in this category. This high material impact was due to the production of maize for starch-polyester and specifically the release of metolachlor during cultivation which contributed over 70% to the bio-based bag's impact.

5.1.10 Marine aquatic ecotoxicity

133 The results for marine aquatic ecotoxicity show that the conventional and oxo-biodegradable bags had a 76% lower impact when compared to the bio-based bag. The difference between the oxo-biodegradable and conventional bags was again found to be insignificant at 0.01%. The reason for the bio-based bag's poor performance in this category was again due to its greater use of material, which contributed 60% to its overall impact. This was due to a number of factors the most dominant of which was the release of barite and barium to water for the use of light fuel oil in starch-polyester production which contributed 22% of the bio-based bag's overall impact.

5.1.11 Terrestrial ecotoxicity

134 The bio-based bag was found to be more than 7 times worse than the other alternatives in terms of terrestrial ecotoxicity with 75% of its impact due to the production of the bio-based. This significant material impact was due to the use of grid electricity during starch-polyester production and the cultivation of the maize used in its manufacture. The grid electricity impact was due to the release of vanadium during the burning of heavy fuel oil while the impact of the maize was due to the release of mercury and cypermethrin during cultivation. The impact of the conventional and oxo-biodegradable bags was dominated by the production impact and specifically the impact of grid electricity use during bag manufacture.

5.2 Sensitivity analysis

135 Several aspects were varied in a sensitivity analysis to understand the effect of changes to the bags' life cycles. The sensitivity analysis investigated the effect of 100% landfill, 100% litter and 100% incineration, and the inclusion of a 50% recycled content for the conventional and oxo-biodegradable carrier bags. The following sections outline the changes made during this sensitivity analysis and their resultant impact on the study's results.

5.2.1 The effect of 100% landfill, litter and incineration at end of life

136 During the impact assessment it was found that, in terms of global warming potential, the bio-based bag had 5 times the impact of the conventional and oxo-biodegradable bags during disposal. This life cycle stage was therefore found to be a key differentiating factor between conventional, oxo-biodegradable and bio-based bags. To understand the influence of each disposal route (i.e. landfill, incineration and litter) a sensitivity analysis was conducted to assess the impact of

each option on the global warming potential of each bag. Figure 8 shows the results of this analysis for a 100% landfill route, a 100% incineration route and a 100% litter route.

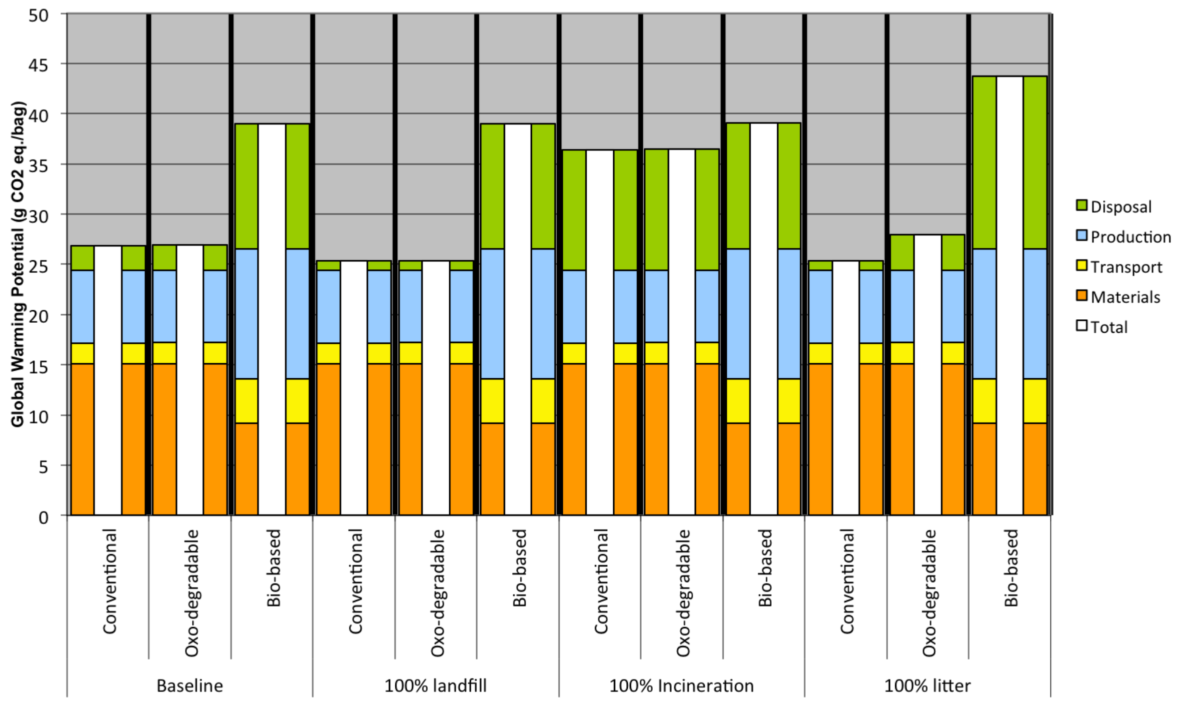

Figure 8, The impact of each disposal route on the GWP of each bag.

137 The results show that in each scenario the bio-based bag was the worst option. For landfill this was due to the degradation of the bio-based bag in an anaerobic environment and the subsequent release of methane. Although methane capture was included in the study, it did not reduce the emissions enough to make the bio-based bag competitive. Both the conventional and oxo-biodegradable bags were considered not to degrade in anaerobic conditions and therefore the landfill of these bags reduced their impact in comparison with the baseline.

138 In terms of 100% incineration the end of life impacts were relatively similar. The incineration of polyethylene generated approximately 3 kg CO2 eq. per kg of material while the incineration of the bio-based material generated 1.9 kg CO2 eq. per kg. However, due to the difference in weight between the bags and the difference in energy recovered per kg, the overall impact of each bag was very similar, ranging from 12.0g to 12.5g CO2 eq. per bag.

139 The bio-based bag performance when littered in the open environment was the worst for any of the scenarios considered in terms of global warming potential. In this scenario there was no gas capture or energy recovery as seen in the landfill and incineration scenarios, and although there were no methane emissions either, the release of 88% of the bag's carbon as carbon dioxide had the largest impact of any life cycle stage. The oxo-biodegradable bag also had its poorest performance in terms of global warming in this scenario due to the release of 15% of the bag's carbon as carbon dioxide. However, this was not to the level of the bio-based bag.

140 The global warming impact of litter must also be taken in context with the litter effects impact category which found both the oxo-biodegradable and bio-based bags to be significantly better than the conventional bag. The degradation relevant to the litter effects category is the abiotic degradation of the material which consequentially removes the bag's visual impact as litter, and removes the bag's potential to block drains or entangle wildlife. This is different to the aerobic biodegradation stage which occurs after abiotic degradation and converts the material to carbon dioxide and water.

5.2.2 The effect of the inclusion of a 50% recycled content for the conventional and oxo-biodegradable carrier bags

141 Many conventional and oxo-biodegradable carrier bags in use today contain a large quantity of recycled material, but the thickness of the bag will often have to be increased to achieve equivalent properties, depending on the proportion and source of the recyclate. To understand the potential influence of a recycled content, a 50% recycled HDPE content was added to both the oxo-biodegradable and conventional bags. The results for 10 of the 11 categories considered are shown in figures 9 and 10 overleaf (litter effects was excluded as it remained the same). The figures show that a recycled content had a positive effect on only 3 of the 10 categories considered. The inclusion of a 50% recycled content reduced the impact of the conventional and oxo-biodegradable bags by 19% in terms of global warming, 40% in terms of abiotic depletion and 16% in terms of photochemical oxidation. However, the recycled content had a negative effect on the other 7 categories, most notably ozone layer depletion, human toxicity, terrestrial ecotoxicity and marine aquatic ecotoxicity. These higher impacts were primarily driven by the increase in shipping included in the bag life cycles to collect and transport recyclable material to China for recycling prior to use within the product and the impact of grid electricity in China for the recycling process.

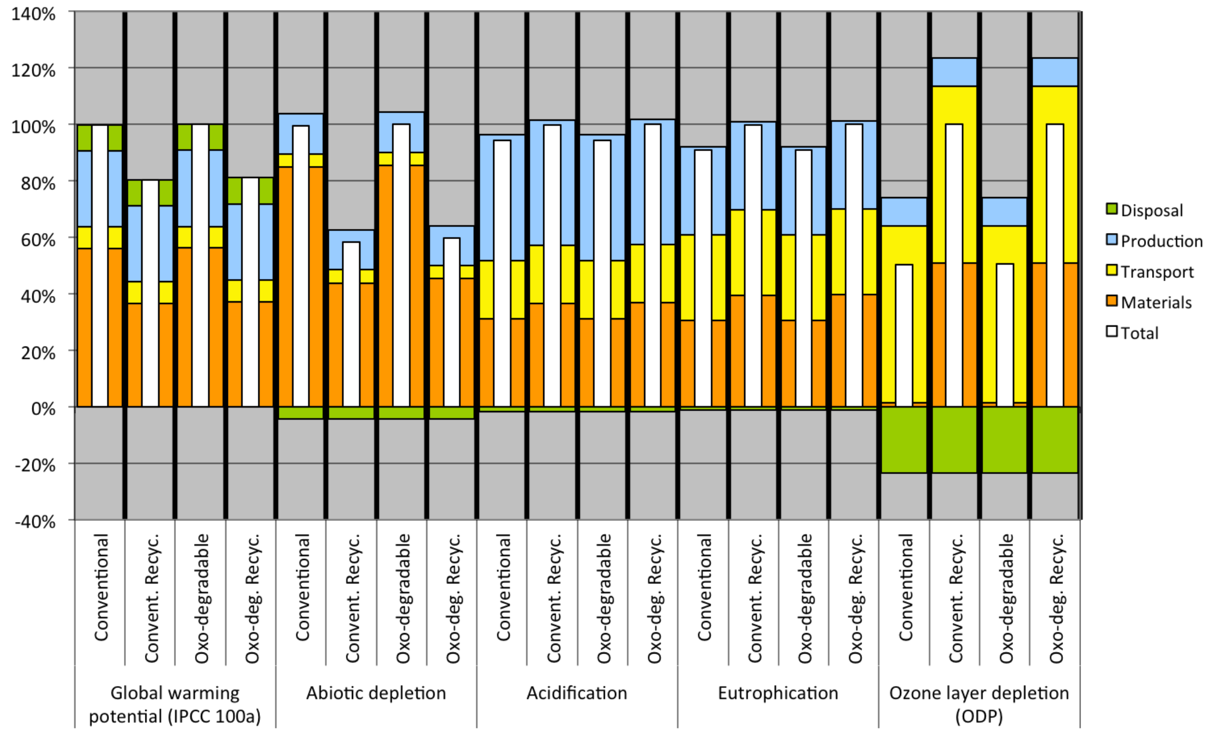

Figure 9, The impact of the inclusion of recycled content on 5 impact categories.

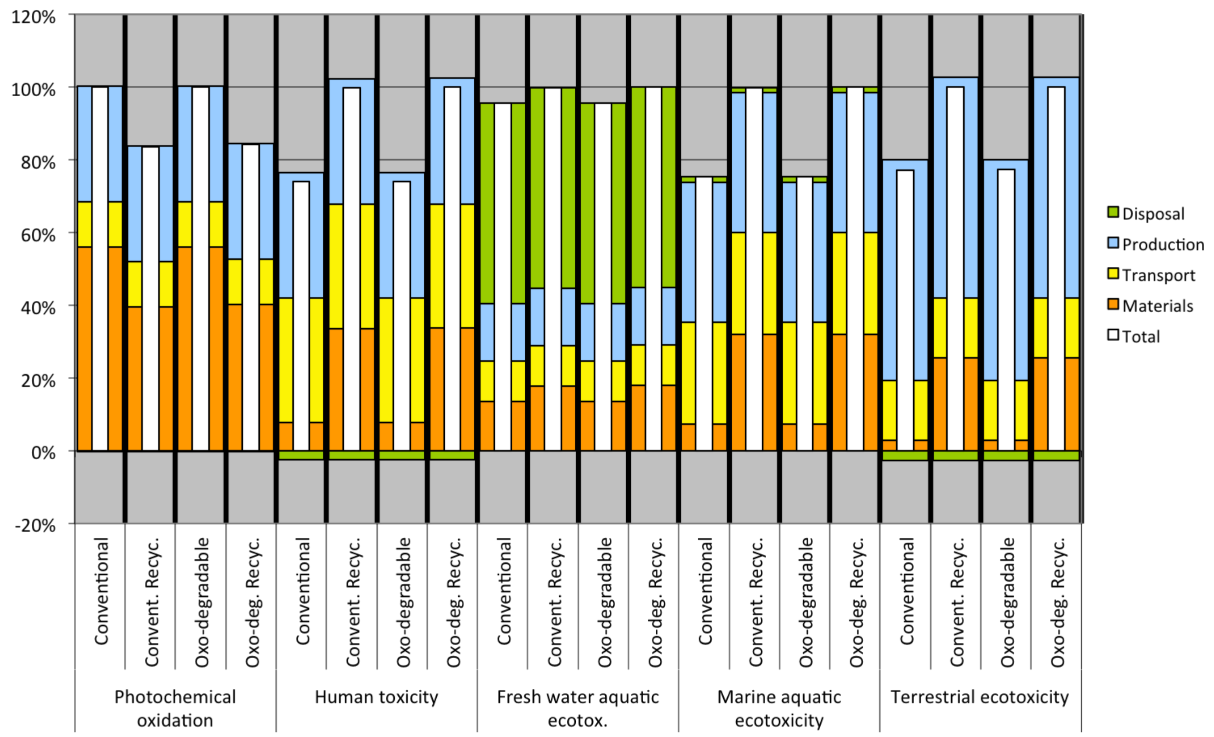

Figure 10, The impact of the inclusion of recycled content on 5 impact categories.

6 Conclusion

142 The results of this LCA have shown that except in relation to litter the environmental difference between oxo-biodegradable and conventional bags is negligible. The largest margin of difference was found to be just 0.55% due to the bags' similarity in terms of functionality, weight, material content and production energy. However, when the litter effects category is also considered, it is clear that the oxo-biodegradable bag has a significant advantage over the conventional bag through its ability to degrade in the open environment. Although only 0.75% of bags enter the litter stream (as estimated in this study), this nevertheless equates to over 48 million bags a year. This means that the superior performance of the oxo-biodegradable bag in terms of litter offers real societal benefit.

143 The global warming potential (carbon footprint) of both HDPE bags was found to be 26.9 grams CO2 eq. per bag, or 3.3 kg CO2 eq. per kilogram. Although this is higher than reported by previous LCA studies, the majority of these studies included a significant benefit from reuse. For example, Edwards & Fry (2011) found that the impact of a conventional bag with no reuse was 3.12kg CO2 per kg and that the inclusion of reuse reduced this impact by 24%. Therefore, if the same amount of reuse was included for this study, the global warming of the conventional and oxo-biodegradable bags would drop to 20.4 g CO2 eq. per bag. The sensitivity analysis also found that the inclusion of 50% recycled content reduced the global warming impact of the conventional and oxo-biodegradable carrier bags by 19%. However, the recycled content also had a negative effect on 7 of the impact categories, due mostly to extra transportation rather than any harmful effects from recycling itself. These results show that the best way to reduce the impact of these bags is to make them oxo-biodegradable, increase their re-use, increase their recycled content and minimise any transportation for recycling.

144 The bio-based bag was found to be worse than the conventional and oxo-biodegradable bags in 10 of the 11 impact categories. The bio-based bag was found to have a global warming potential of 39 grams CO2 eq. per bag, 45% higher than the conventional and oxo-biodegradable bags. However, there were a number of assumptions made within the life cycle of that bag that contain a degree of uncertainty. These assumptions included a 30% greater weight to achieve the same functionality as conventional bags (although in reality the additional weight may need to be more than 30% to achieve comparable strength), a 38% higher energy consumption during bag production, the exportation of starch-polyester from Italy to China, and assumptions regarding the degradation of the bag in landfill.

145 The sensitivity analysis on disposal methods showed that the bio-based bag has a greater impact on global warming in the conventional forms of disposal (landfill, incineration) when compared to the conventional plastics due to its biodegradation. The bio-based bag's impact during anaerobic degradation was assumed to be significantly higher than the other alternatives, making the bag worse in terms of landfill and litter despite the recovery of energy at some landfill sites. These results show that the benefit of biogenic carbon dioxide absorption during crop growth can

have a negative effect on impact categories such as global warming if the bio-based bag is not disposed of via composting, for which it is designed.

146 Overall the results can be summarised as follows:

- 146.1 The conventional bag and oxo-biodegradable bag were found to be the same in all environmental impact categories (any differences were well under 1%), except in the litter category where the oxo-biodegradable bag was 75% better.
- 146.2 The global warming potential (carbon footprint) of a conventional or oxo-biodegradable carrier bag was found to be 26.9 grams CO2 eq.
- 146.3 The inclusion of 50% recycled content in the conventional and oxo-biodegradable carrier bags would reduce their impact by 19% in terms of global warming but would have a negative impact on 7 of the other environmental impact categories due to increased shipping.
- 146.4 The bio-based bag was the worst option in 10 of the 11 environmental impact categories due to its higher bag weight and thickness, increased energy consumption, greater transportation and higher end of life impacts.

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Appendix A: Description of impact categories

Global warming

170 **What is it?** Global warming potential is a measure of how much of a given mass of a green house gas (for example, CO_2, methane, nitrous oxide) is estimated to potentially contribute to global warming. Global warming occurs due to an increase in the atmospheric concentration of greenhouse gases which changes the absorption of infra red radiation in the atmosphere, known as radiative forcing, leading to probable changes in climatic patterns and higher global average temperatures.

171 **Why is it an issue?** If no action is taken to reduce global carbon emissions, average temperatures are predicted to rise by more than 2 degrees Celsius. This change is likely to increase severe weather such as tropical storms, droughts, heat waves and heavy precipitation. Stabilisation would require emissions to be at least 25% below current levels by 2050.

172 **How is it measured?** Global warming potential is measured in terms of CO_2 equivalents.

Litter Effects

173 **What is it?** "Litter effects" is a measure of the visual impact of litter and is based on the area of litter and the time taken for that litter to disappear to the naked eye (break up into tiny fragments).

174 **Why is it an issue?** Litter has become an increasing issue world wide and it is a social concern. In addition to visual effects plastic litter can also block drains and harm wildlife.

175 **How is it measured?** Area in square metres multiplied by visible time in years (m2.a)

Abiotic depletion

176 **What is it?** This impact category refers to the depletion of non living (abiotic) resources such as fossil fuels, minerals, metals, clay and peat.

177 **Why is it an issue?** In 2006, WWF International reported that man's impact on global resources has tripled since 1961 and is now 25% above the planet's ability to regenerate itself. If the world's population shared a western lifestyle, three planets would be required to meet their needs.

178 **How is it measured?** Abiotic depletion is measured in kilograms of Antimony (Sb) equivalents.

Ozone layer depletion

179 **What is it?** Changes to atmospheric ozone will modify the amount of harmful UV radiation penetrating the earth's surface with potential adverse effects on human health and ecosystems.

180 **Why is it an issue?** An increase in UV increases the risk of skin cancer as well as additional risks to human health. Even though the Montreal Protocol has reduced CFC emissions, the complete recovery of the Antarctic ozone layer will not occur till after 2050.

181 **How is it measured?** Ozone layer depletion is measured in terms of CFC equivalents.

Photochemical oxidation

182 **What is it?** The formation of photochemical oxidant smog is the result of complex reactions between NOx and VOCs under the action of sunlight (UV radiation) which leads to the formation of ozone in the troposphere. The smog phenomenon is very dependent on meteorological conditions and the background concentrations of pollutants.

183 **Why is it an issue?** These substances are characteristic of photochemical smog (summer smog or Los Angeles smog), a known cause of health problems such as irritation to respiratory systems and damage to vegetation.

184 **How is it measured?** It is measured using photo-oxidant creation potential (POCP) which is normally expressed in ethylene equivalents.

Eutrophication

185 **What is it?** This is caused by the addition of nutrients to a soil or water system which leads to an increase in biomass, damaging other lifeforms. Nitrogen and phosphorus are the two nutrients most implicated in eutrophication.

186 **Why is it an issue?** Eutrophication was recognised as a pollution problem in European and North American lakes and reservoirs in the mid-20th century. Surveys showed that 54% of lakes in Asia are eutrophic; in Europe 53%; in North America 48%; in South America 41%; and in Africa 28%.

187 **How is it measured?** Eutrophication is measured in terms of phosphate (PO_4^{3-}) equivalents.

Acidification

188 **What is it?** This results from the deposition of acids which leads to a decrease in the pH, a decrease in the mineral content of soil and increased concentrations of potentially toxic elements in the soil solution. The major acidifying pollutants are SO_2, NOx, HCL and NH_3.

189 **Why is it an issue?** Examples of impacts are fish mortality in lakes, leaching of toxic metals out of soil and rocks, damage to forests and damage to buildings and monuments.

190 **How is it measured?** Acidification is measured in terms of SO2 equivalents.

Toxicity

191 **What is it?** Toxicity is the degree to which something is able to produce illness or damage to an exposed organism. There are 4 different types of toxicity; human toxicity, terrestrial ecotoxicity, marine aquatic ecotoxicity and fresh water aquatic ecotoxicity.

192 **How is it measured?** Toxicity is measured in terms of dichlorobenzene equivalents.

Appendix B: Life cycle diagrams

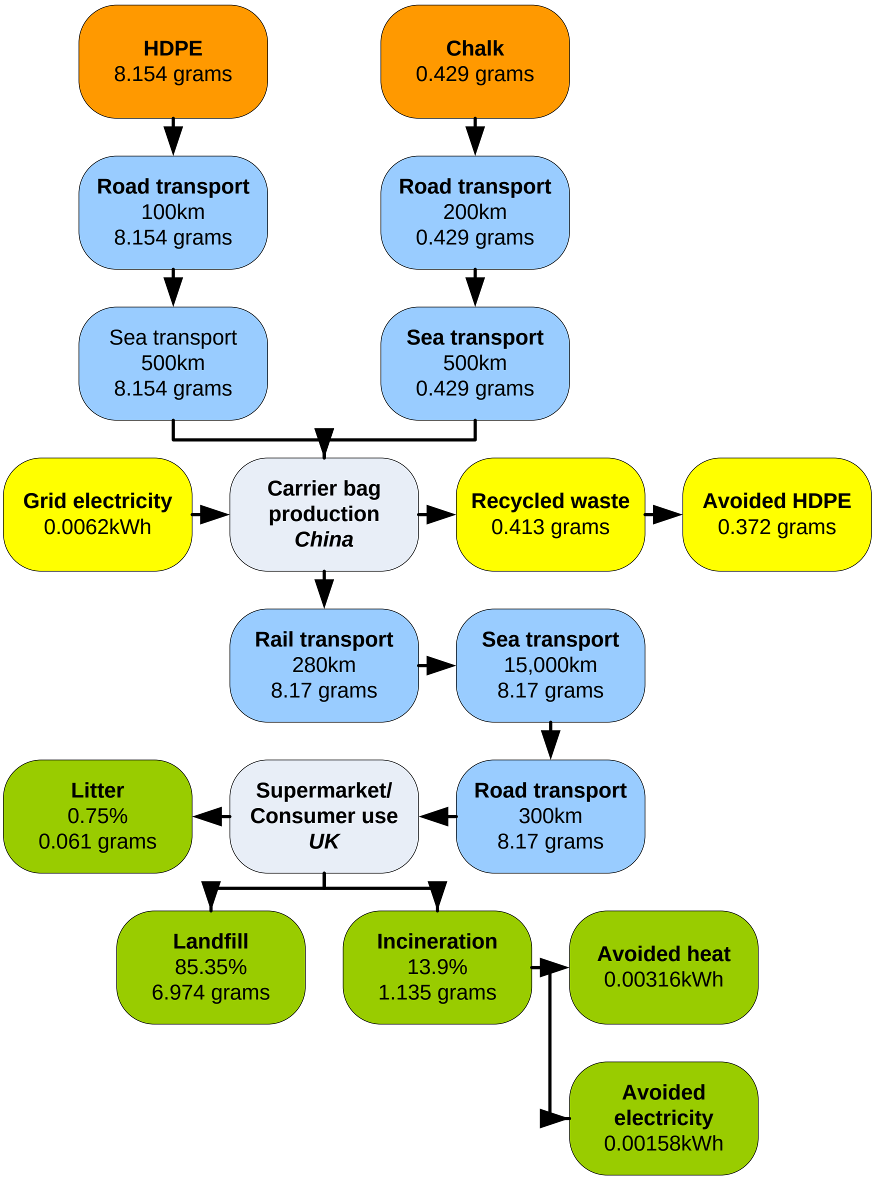

Figure B1, The life cycle of a 19.1 litre conventional HDPE carrier bag.

Intertek

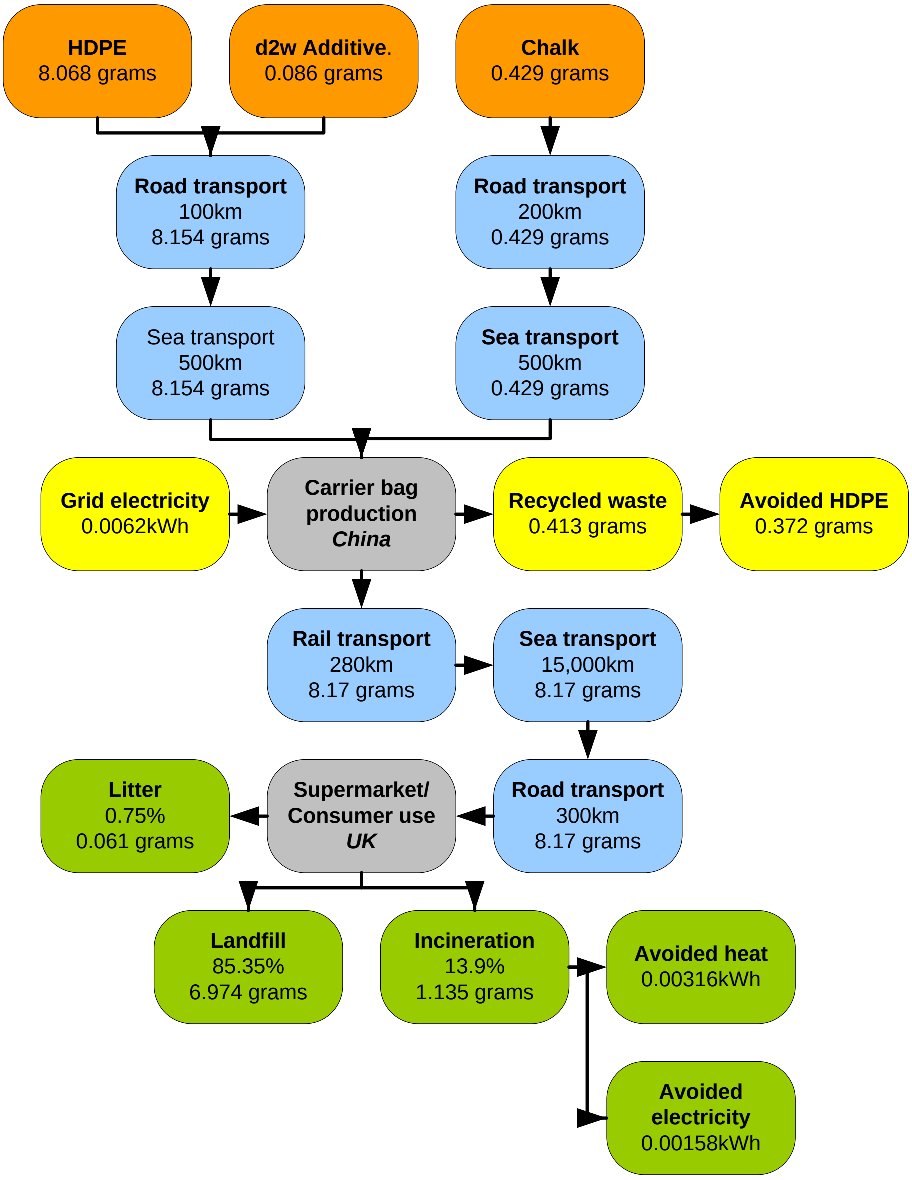

Figure B2, The life cycle of a 19.1 litre oxo-biodegradable HDPE carrier bag.

Figure B3, The life cycle of a 19.1 litre bio-based carrier bag.