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Single-use plastic bags and their alternatives

Recommendations from Life Cycle Assessments

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Executive summary

Single-use plastic bags (SUPBs) are one of the most consumed items globally and much debate has evolved around their environmental impact. However, their alternatives for shopping – e.g. cotton and paper bags – also come with an environmental footprint, and do not necessarily outperform plastic bags in all environmental categories. To identify which solution is environmentally more sustainable, the impact of SUPBs compared to their alternatives needs to be investigated under a life cycle perspective. Life cycle assessment (LCA) is a quantitative tool designed for this purpose, to assess the environmental impacts of products and services across their full life cycle including raw material extraction, production, logistics and distribution, use and end-of-life.

A meta-analysis of seven LCAs published in English since the year 2010 was conducted to investigate what can be learnt from these studies, and to provide guidance to policy makers and other actors on how to interpret results from comparative LCAs on shopping bags. The table below summarises the findings, including the environmental benefits and drawbacks of SUPBs compared to other bags. The report also sheds light on the benefits and challenges of LCA as a method to assess the environmental aspects of bags. Based on the learnings from this meta-analysis, the report provides guidance for experts undertaking future LCAs of plastic bags and their alternatives to improve the comprehensiveness, consistency and accuracy of the analysis.

The main conclusions indicated by the seven studies are the following:

- The material type and weight of a shopping bag are important characteristics for determining its environmental impacts. A bag with the same material but double the weight has double the impact, unless it is reused more times or used to carry more goods. The LCAs in the meta-analysis indicate that a SUPB weighs approximately 6 g in China, India, Singapore and the US, but 18-20 g in Finland, Spain and the UK.
- The number of times a bag is used directly influences its environmental impacts. For instance, if a bag is used for shopping twice instead of once, it has only half the environmental impact per shopping round.
- The technology and material/energy use of production processes influence the impact of bags. For example, the climate impact of paper bags varies greatly, depending on what fuel is used in the pulp and paper production.
- The waste-management process also influences the environmental impact of bags. Paper bags that end up in landfills cause emissions of methane with high climate change effect, while plastic bags are relatively inert. On the other hand, incineration of used plastic bags affects the climate through emissions of fossil carbon dioxide (CO_2), while the CO_2 emitted from incineration of paper bags is part of the natural carbon cycle. The environmental impacts of biodegradable bags are reduced if the bags are composted, while most other bags benefit from material recycling.

- Considering the impacts from all life cycle stages, the environmental ranking of bags varies between different environmental categories. The SUPB is a poor option in terms of litter on land, marine litter and microplastics, but it scores well in other environmental impact categories, such as climate change, acidification, eutrophication, water use and land use. The overall environmental ranking will depend on what environmental aspects are given the highest priority. In this context it might be important to note that bags are responsible for a significant share of the litter, but a very small share of the total climate change when compared with other products and commodities.
- Reusable bags can be environmentally superior to SUPBs, if they are reused many times. For example, a cotton bag needs to be used 50-150 times to have less impact on the climate compared to one SUPB. A thick and durable polypropylene (PP) bag must be used for an estimated 10-20 times, and a slimmer but still reusable polyethylene (PE) bag 5-10 times, to have the same climate impacts as a SUPB. This requires not only durability of the bags, but also consumers to reuse each bag many times.
- Paper bags contribute less to the impacts of littering but in most cases have a larger impact on the climate, eutrophication and acidification, compared to SUPBs. However, they can be better for the climate if the SUPB is heavy, the paper mills use renewable fuel, the paper bags are reused multiple times, and/or the waste bags are incinerated rather than deposited at landfills.
- Single-use polyethylene bags based on renewable resources are better for the climate, compared to conventional SUPBs; however, they cause the same problems related to impacts of littering and are likely to cause more acidification and eutrophication.
- Biodegradable bags decompose and contribute less to the impacts of littering, compared to conventional SUPBs; however, the LCA results indicate they might be the worst option when it comes to climate impacts, acidification, eutrophication, and toxic emissions.
- A plastic bag with a prodegradant additive (oxo-degradable bag) has almost identical impacts compared to the conventional SUPB. It has less visual impact as litter, because it degrades into small fragments. However, the problem of microplastics might still remain, and the prodegradant can cause problems in recycling processes.

When using these findings for decisions, it should be noted that the production processes of innovative materials such as bio-based or degradable plastic bags are relatively new and might improve significantly over time. Most of the seven LCAs are 5-10 years old and some of the input data used in the studies are significantly older.

It can be concluded that reducing environmental impacts of bags is not just about choosing, banning, recommending or prescribing specific materials or bags, but also about changing consumer behaviour to increase the reuse rate and to avoid littering. The shopping bag that has the least impact on the environment is the bag the consumer already has at home.

Summary from all studies (by different environmental impact categories)

	Environmental impact category in the life cycle of the bags					
	Climate change	**Acidification**	**Eutrophication**	**Photochemical ozone**	**Land use change**	**Littering Potential**
Conditions or other observations	• In the majority of reviewed studies, PE based plastic bags were found to have the lowest climate impact. • Single use PE bags from recycled or bio-based materials were found to have a lower climate impact than their fossil PE alternative. • Durable PP and reusable PE bags need to be reused 10-20 and 5-10 times, respectively before they can compete on the basis of climate change with single-use bags. This is due to their higher weight and the related material consumption. • Paper bags can be better for the climate if produced in integrated mills using renewable energy and if bags are reused and recycled or incinerated. Forestry can affect the carbon stocks above and below ground. This effect can be considerable, potentially leading to a high climate impact or a climate benefit, depending on the forest management. • Cotton bags need to be reused 50-150 times followed by incineration or recycling before their climate impact is comparable to single-use plastic bags.	• While all reviewed studies assessed climate impact, the assessment for other impacts such as acidification, eutrophication and ozone related impacts varied between studies. • For the studies that assessed acidification, eutrophication and ozone related impacts, fossil PE-based alternatives (HDPE/LDPE) were found to be the best option. There is no clear 'worse' alternative, though the studies point towards bio-based alternatives. • Bio-based LDPE was found to perform worse than fossil LDPE. • For durable and reusable LDPE and PP bags, as well as cotton and paper bags the same findings as for climate change apply: whether they can compete with the single use alternatives depends on the number of reuses. • Starch-based bags were found to have no environmental benefit compared to conventional single use bags.			• Though not assessed in detail, it is important to consider that bio-based and paper bags require a certain amount of land for feedstock cultivation. • In addition to land use, there is also the possibility of land use change which can lead to impacts on biodiversity, etc.	• There are several impacts of littering: visual impacts, physical impacts on animals, and the impacts of microplastics. • The assessment of littering potential in LCA is still under development. A minority of the reviewed studies addresses impacts of littering and even these account for visual impacts only. • Littering potential is a challenge for non-degradable bags (fossil- and bio-based) and for bags labeled as degradable. • Bio-degradable plastics should not just be left in the environment, handling in managed sites is needed. • The degradation rate depends on the local conditions. Exposure to UV light, availability of oxygen, temperature, and humidity influence the degradation process of degradable plastics, paper and cotton. • Oxo-degradable plastics seem to only partially fragment, i.e. they leave residues behind.

This table summarises the comparative analysis and findings for the references used in this study. These results are summarised and do not include sensitivity analyses, please refer to Chapter 3 for more detailed results.

Study	Climate change		Acidification		Eutrophication		Ozone impacts		Land use change		Littering Potential		Comments
	Best	Worst	Best	Worst	Best	Worst	Best	Worst	Best	Worst	Best	Worst	
1. Civancik-Uslu et al. (2019)	Reusable LDPE bag	Paper bag	Conventional HDPE bag	PP bag	Conventional HDPE bag, reusable LDPE bag	Paper bag	Conventional HDPE bag, reusable LDPE bag	PP bag	N/A	N/A	PP bag	Conventional HDPE bag	• The reusable LDPE bag is assumed to be used 10 times. • The ranking in terms of littering potential is more or less opposite to ranking of other indicators • Credits for reuse as bin liners for HDPE and degradable bags are included. • The study did not account for virgin material production substituted through recycling. • The study did not distinguish between the bags depending on their size, assumed that the same quantity of bags is used for shopping (despite their different capacities).
2. COWI A/S and Utrecht University (2018)	Bio-based LDPE bag	Conventional LDPE bag, biodegradable bag	Conventional LDPE bag	Bio-based LDPE bag	Conventional LDPE bag	Bio-based LDPE bag	Conventional LDPE bag, biodegradable bag	Bio-based LDPE bag	Taken into consideration under climate change	Taken into consideration under climate change	N/A	N/A	• When indirect land-use changes are accounted for, the climate impact of the bio-based bag increases significantly but is still much smaller than the impacts of the conventional plastic bag. • Results change when calculations are made with the theoretical assumption of 100% recycling/composting, incineration, and landfilling.

3. Kimmel (2014)	Reusable LDPE bag (near 44 times reuse)	Paper bag (single use)	Reusable LDPE bag (near 44 times reuse)	Paper bag (single use)	Reusable LDPE bag (near 44 times reuse)	Paper bag (single use)	Conventional single use HDPE bag, partly recycled single use HDPE bag, Reusable LDPE bag (near 44 times reuse)	Paper bag (single use)	N/A	N/A	N/A	N/A	• Results change depending on different scenarios that have been tested in the study (reuse 1-44 times, with/without secondary use). • The reusable LDPE and NWPP bags will have lower average impacts, compared to SUPBs, if they are reused for a sufficient number of times (6-9 times for the LDPE “wavetop” bag and 13-20 times for the NWPP bag). The paper bags must be used 3.7-5.4 times, depending on the content of the paper and on whether the second life is included. • The reuse rate is less than sufficient for the majority of US consumers.
4.1. Edwards and Fry (2011)	HDPE bag, paper bag	starch and polyester based bag	LDPE bag	starch and polyester based bag	HDPE bag, LDPE bag	starch and polyester based bag	LDPE bag	starch and polyester based bag	N/A	N/A	N/A	N/A	• The study assumes that part of the lightweight carrier bags are reused as kitchen bin liners. • The LCA results are sensitive to the amount of material in the bag, the rate of reuse in shopping and secondary reuse at home, and the waste management.
4.2. Edwards, Parker (2012)	HDPE with prodegradant additive bag, HDPE bag	starch and polyester based bag	HDPE with prodegradant additive bag, HDPE bag	starch and polyester based bag	HDPE with prodegradant additive bag, HDPE bag	starch and polyester based bag	HDPE with prodegradant additive bag, HDPE bag	starch and polyester based bag	N/A	N/A	starch and polyester based bag, HDPE bag	HDPE bag	• The study found almost exactly the same environmental impacts for the oxo-degradable and conventional HPDE bags, except for littering potential, where the degradable bag is much better. •Recycling, composting, reuse have been excluded. • It was assumed that the impact of oxo-biodegradable plastics in landfill is the same as that of conventional plastics, with no anaerobic degradation.

5. Muthu et al. (2011, 2012)	NWPP bag	Single-use Paper bag	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	• The consumption of material influences the results; a low material consumption for durable bags has a lowering effect on their environmental impact. • High reuse rate reduces the environmental impact of the bags (assumption durable PP replaces 100 single use bags, cotton bags replace 50 single use plastic bags).
6. Mattilla et al. (2011)	RPE (60% recycled PE) bag	Biodegradable bag	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	• The way how landfilling conditions (methane recovery or not) are assessed influences the preferability of the bags. • Paper bags and biodegradable bags need methane recovery under landfilling, otherwise they have a high impact. • Waste incineration is a better option for paper and cotton (carbon neutral). • High replacement rates lower the environmental impact (assumption cotton bags replace 100 single use plastic bags). • The energy used during paper production can have a significant effect on the paper bag impact (low emission energy lowers the impact).
7. Khoo et al. (201)	Single-use fossil-based bag	Single-use PHA bag	Fossil based bag	PHA bag	Fossil based bag	PHA bag	Fossil based bag	PHA bag	N/A	N/A	N/A	N/A	• The bio-based bag is modeled with a lower carrying capacity than the fossil alternative - more material is needed per bag. • The impact of the bio-based bag is completely dominated by the energy supply during production (energy supply with high emissions).

In addition to the above summarised findings, the review provided some general findings, which are presented below.

Critical parameters influencing the results:

- The number of uses greatly influences LCA results: increased number of uses (for shopping and eventually as bin liner) will reduce the impacts of all products.
- The final waste-management option is decisive: incineration or efficient sorting including recovery can positively influence the environmental impacts of cotton and paper bags. The LCAs indicate that landfilling is the least preferred option for cotton, paper and biodegradable bags as degradation releases methane, which has a strong impact on the climate.
- The age of the data and of the technology being assessed needs to be considered. The production of conventional plastics is a mature and large-scale technology, which makes the age of these data less critical. However, new and innovative plastics, including bio-based alternatives, are still at the beginning of their improvement curve, therefore recent data are important as the technology and scale of production might change significantly over time.

Recommendations for policy makers and other strategic decision-makers:

Selecting bag types:

- Bags that are designed for multiple uses (reuse) have lower impacts than SUPBs in most environmental impact categories, if they are actually used a sufficient number of times (50-150 times for cotton bags, 4-8 times for paper bags, 5-10 times for reusable LDPE bags for, and 10-20 times for durable, non-woven PP bags). These numbers might not be reached, depending on consumer behaviour etc.
- Banning single-use plastic bags while favouring other single-use alternatives results in environmental trade-offs. For example, single-use paper bags have less impact of littering, compared to SUPBs, but often have higher impact on most other environmental categories (Climate Change, Acidification, Eutrophication, Ozone Depletion, Land use change). When defining policies on bags, these trade-offs should be evaluated in the specific geographical context.
- In countries with under-developed waste-management systems and poor infrastructure for collection and recycling, the arguments against SUPBs are stronger because littering and its associated environmental impacts are greater. Reusable and degradable alternatives, such as cotton or paper bags, should be considered as options to reduce these impacts.
- In countries where incineration is prevalent as a waste-treatment approach (with or without energy recovery), paper, cotton, and other bio-based bags with no fossil co-polymers have the advantage of climate-neutral incineration. They might have a lower total impact on the climate compared to conventional SUPDs, particularly when the materials are produced with renewable process energy and the bags are sufficiently reused.

- Bio-based bags do not guarantee a lower environmental impact. To achieve a lower impact, they need to be reused, which requires a reusable design and also incentives and consumer awareness for reuse. Also, biomass production (forestry and agriculture) needs to be sustainably operated and low-emission energy has to be used in the production processes. The use of fossil-based co-polymers in bio-based plastic bags needs to be reduced or avoided. If they are compostable, segregated organic waste collection should be in place and waste bags sent to composting.

Consumption and user behaviour

- Re-use of all types of bags needs to be promoted, as this extends the lifetime of bags and reduces impacts from the production of new bags as well as the waste management. Durable bags, such as higher quality plastic bags and cotton bags, have greater environmental impacts in the production stage; however, if consumers use them a sufficient number of times, a shift to durable bags can bring significant environmental benefits.
- Incentives and education need to be provided to consumers to reduce their consumption of bags. Alternatives (such as reusable bags), clear consumer information, sensitization and communication need to be in place for consumers to reduce or avoid the use of single-use bags.
- Campaigns and educational programmes need to be provided to students and citizens to minimize the littering of bags (especially plastic bags), as well as other impactful behaviours such as dumping and open burning of plastic bags.

Management of end-of-life bags

- Recycling of bags in state-of-the-art facilities reduces the impacts in the end-of-life phase, and always reduces the use of raw materials for producing new bags.
- The collection and sorting systems need to be able to effectively segregate degradable plastic bags from non-degradable bags, and use corresponding processing and recycling technologies for effective treatment.
- In countries where sanitary landfills are a prevalent approach for waste disposal, landfill gas should be collected to reduce impacts to the climate. This also reduces the climate impacts of degradable bags (e.g., paper and cotton).
- Systems to prevent conventional plastics (fossil and bio-based) from entering the biological waste treatment stream need to be in place, as conventional plastics can: (1) clog treatment processes, and (2) end up on/in soil as part of the compost (conventional plastics do not degrade in biological processes and leave residues behind). For example, the bio-degradable bags used for collection biological waste should look distinctly different from non-degradable plastic bags.

Recommendations on what to consider when using LCAs for decision making on shopping bags:

The results of LCAs depend on the specific choices made in the study regarding, for example, system boundaries and input data. A transparent LCA report includes information on the important methodological choices. However, it can be difficult for a non-LCA expert to understand the reasons for making these choices and to assess the relevance of the system boundaries etc. It is recommended that LCA experts are involved in interpreting results. They will be able to clarify what kind of knowledge can be gained from the given LCA and why another LCA can generate different results.

A one-on-one comparison of bags with different sizes is not accurate, because consumers might need a larger number of bags if they are smaller. On the other hand, the functionality of the bags is also not accurately reflected by their capacity, because a small bag is often a sufficient substitute for a larger bag. The most accurate comparison is somewhere between the two.

The LCA should include country-specific data, particularly on the waste-management system, the weight of the bags and the number of times each bag is used, because these factors vary between countries and have an important impact on the LCA results.

The input data should be as recent as possible. This is particularly important for modelling the production of innovative materials, because of the rapid changes that can occur in new technological processes.

There is a need for the LCA community to develop the impact assessment framework to integrate the impacts of littering (including marine litter). The project MariLCA (http://marilca.org/) has been launched to fill this gap.

Glossary

Term	Definition
ALCA (accounting/attributional LCA)	A type of LCA that gives an estimate of which part of the global environmental burdens belongs to the study object.
Bio-based plastics	A type of plastic derived from biomass such as organic waste material or crops grown specifically for the purpose, which may or may not be biodegradable (UNEP, 2015).
Bio-plastics	A term commonly used to describe both biodegradable plastics and bio-based plastics (UNEP, 2015).
Biodegradable	Capable of biodegrading under biological process of organic matter, which is completely or partially converted to water, CO2/methane, energy and new biomass by microorganisms (bacteria and fungi) (UNEP, 2015).
Biopolymer	A type of polymer produced from natural sources.
CLCA (consequential/change-oriented LCA)	A type of LCA that gives an estimate of how the production and use of the study object affect the global environmental burdens.
Compostable	Capable of biodegrading at elevated temperatures in soil under specified conditions and time scales, usually only encountered in an industrial composter (standards apply) (UNEP, 2015).
Degradable	Capable of a partial or complete breakdown as a result of e.g. UV radiation, oxygen attack, biological attack, which implies alteration of the properties, such as discolouration, surface cracking, and fragmentation (UNEP, 2015).
HDPE (High-density Polyethylene)	High-Density Polyethylene is a thermoplastic polymer, produced from either fossil or renewable resources. Known for its strength, HDPE plastic has a high-impact resistance

	and melting point, commonly used in bags or bottles. HDPE does not degrade in biological waste processes, such as aerobic composting, anaerobic digestion or mechanical-biological treatment (MBT).
LCA (Life Cycle Assessment)	Compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle (ISO 14040:2006 and 14044:2006).
LDPE (Low-Density Polyethylene)	Low-Density Polyethylene is a thermoplastic polymer produced from either fossil or renewable resources. It is strong, flexible and relatively transparent, hence used in bags or stretch films. LDPE does not degrade in biological waste processes, such as aerobic composting, anaerobic digestion or mechanical-biological treatment (MBT).
Lightweight plastic carrier bags	Plastic carrier bags with a wall thickness below 50 microns.
Microplastics	Generic term for small pieces of plastic under 5 mm (UN Environment, 2018).
Oxo-degradable	Containing a pro-oxidant that induces degradation under favourable conditions. Complete breakdown of the polymers and biodegradation still have to be proven (UNEP, 2015).
PHA (polyhydroxyalkanoates)	PHA is a type of biodegradable thermoplastic polymer, produced through the fermentation of e.g. sugar or vegetable oils.
Plastic Carrier Bag	Carrier bags, with or without handle, made of plastic, which are supplied to consumers at the point of sale of goods or products (UN Environment, 2018).
PP (Polypropylene)	PP is a thermoplastic polymer often used in packaging and labelling. It has similar properties than polyethylene, but is harder and more heat resistant. PP does not degrade in biological waste processes, such as

	aerobic composting, anaerobic digestion or mechanical-biological treatment (MBT). PP can also be used in different ways to make Non-woven PP (NWPP) and woven PP (WPP) bags, which will have different characterisation, such as strength. (Kimmel, 2014)
PE (Polyethylene)	PE is a hard and rigid thermoplastic, commonly used in packaging such as plastic bags, films, bottles. Conventional polyethylene is produced from fossil fuel feedstock, while bio-polyethylene is produced entirely from biomass feedstock (UNEP, 2015).
Single-use plastics	Commonly used plastic packaging including items intended to be used only once before they are thrown away or recycled, e.g., grocery bags, food packaging, bottles, straws, containers, cups, cutlery, etc. Often also referred to as disposable plastics (UN Environment, 2018).
Single-use plastic bag (SUPB)	Plastic carrier bags that are produced for a single use. This term is used interchangeably with the term “lightweight plastic carrier bags” in this study

1. Introduction

1.1 Background

Plastic is a valuable resource that is used for many applications in our life. It has been estimated that about 348 million tonnes of plastics were produced globally in 2017 (Plastics Europe, 2018), of which about one third is used in single-use plastic products (UN Environment Programme, 2018). Single-use plastic is *“an umbrella term for different types of products that are typically used once before being thrown away or recycled”* (UN Environment Programme, 2018) and includes e.g. food packaging, bottles, straws, containers, cups, cutlery and shopping bags (ibid.).

Shopping bags made of plastic have been described as the world’s number one item used by consumers and have been considered a symbol of a *“throw-away”* society (Napper & Thompson, 2019; UN Environment, 2018). It has been estimated that about 500 billion plastic bags are used worldwide annually with an average service time of 15 minutes (Plastics Oceans, 2019). This leads to negative consequences to the environment such as use of non-renewable resources and impacts of littering.

Which alternative is fit-for-purpose and more sustainable to replace certain single-use plastic products can be quite controversial. It is essential to consider the potential impacts across the full life cycle of a product and its alternatives, and life cycle assessment (LCA) is the tool best suited for this type of comparisons. LCA is a standardized method (ISO, 2006a, 2006b) and quantifies the potential environmental impacts during the whole life cycle of a product: from raw material extraction through production, use, and waste treatment to final disposal). However, this tool has it challenges too, these include: the lack of standardised assessment methods for e.g. litter in the environment (including in the oceans) and the challenge to include the complexity of environmental issues and systems perspectives. It has been also found that there is no harmonisation between most LCA studies. This sometimes leads to contradicting results, and it is essential to understand the full impacts of single-use plastic products based on LCA, with expert guidance on the interpretation.

Policy-makers from around the world have responded to the problem of single-use plastic products by implementing many types of regulations, such as bans, levies or obligations to provide information about the negative environmental impact of plastic bags (Nielsen et al., 2019). It has been observed that during the last 10 years plastic bag policies have spread including to Latin America and the Middle East (Nielsen et al., 2019). The EU Directive (DIRECTIVE (EU) 2015/720, 2015) was the first intergovernmental measure that aimed to decrease the use of lightweight plastic carrier bags (ibid.). Moreover the new Single-Use Plastics Directive (Directive (EU) 2019/904), published in 2019, aims to reduce the impact on the environment of certain plastic products (including lightweight plastic carrier bags) and requests to “take into account the relative properties of different packaging materials, including composite materials, on the basis of life cycle assessments, addressing in particular waste prevention and design for circularity"(DIRECTIVE (EU) 2019/904, 2009).

Published by the United Nations Environment Assembly (UNEA) in March 2019, UNEA4 resolution on "Addressing Single-use plastic products pollution" (UNEP/EA.4/L.10), "encourages member states to take actions, as appropriate, to promote the identification and development of environmentally friendly alternatives to single-use plastic products, taking into account the full life cycle implications of those alternatives". UN Environment Programme was requested by UNEP/EA.4/L.10 to make available existing information on the full life cycle environmental impacts of plastic products compared to products of alternative materials.

Guided by this mandate, this study aims to provide an insight into how LCA can be used to make informed decisions on single-use plastic products and their alternatives. In order to provide insight in a comprehensive manner on this product perceived as problematic by most governments, this study will use the example of single-use plastic bags, for which an extensive amount of data are already available. Other products such as bottles and food take-away packaging will follow in this study series.

1.2 Purpose, scope and method

This report aims to provide guidance to policy makers and other actors on how to interpret results from comparative LCAs on shopping bags. It also summarises what can be concluded on the environmental drawbacks and benefits of plastic bags, compared to other bags, based on existing LCAs. Finally, the report sheds light on the benefits and challenges of LCA as a method to assess the environmental aspects of bags. Based on the learnings from this meta-analysis, the report provides some guidance to those who will in the future conduct an LCA of plastic bags to avoid some of the more common shortcomings and mistakes.

This report considers several alternatives to single-use plastic bags (SUPBs). These include bags that are made from other materials (such as paper, textile, bioplastics, composite), as well as bags that are made from plastics that have a higher durability and/or greater thickness, than lightweight single-use plastics, thus enabling re-use of the bag.

The basis for the report's discussion is a meta-analysis: a review and analysis of selected existing LCA studies that compare SUPBs and their alternatives. Relevant studies were identified from IVL's internal library, Google, Google Scholar, and the LCA discussion list organised by PRe Consultants. Selected studies were then reviewed based on the following criteria:

- **Date of the study**: Production technologies and processes evolve over time, including a potential change in their environmental impact. This factor was taken into account by only considering studies published between 2010 and 2019.
- **Transparency**: Transparency of the studies is necessary to interpret the results and understand what knowledge can be gained from the study. Transparency can be low because it can be difficult to access, or because it includes little information.
- **Relevance of assessed products**: Based on the focus of the project, only studies that assess single-use plastic bags and their alternatives were included. Studies that focus on other single-use plastic products (e.g., packaging, plastic cups, cutlery) or on durable plastic products (e.g., building materials) were excluded from the review.
- **Geographical coverage**: This report is intended to be used globally and the reviewed studies cover this global range to the extent possible.
- **Language:** The report mainly focused on studies published in English. Findings of a study published in Spanish were included in the section on littering potential.
- **Peer reviewed**: Peer review ensures a certain extent of quality, as studies are scrutinised by fellow experts before being published. For this reason, peer-reviewed studies were given priority.

Compliance to international standards, such as ISO 14044:2006, was not used as a selection criterion as the project does not aim at assessing the compliance of studies but rather at explaining their results and extracting the knowledge that can be obtained from them. This is not clearly linked to ISO compliance.

Based on these criteria seven studies were selected for the meta-analysis: four from Europe, two from Asia and one from North America - all published in English since the year 2010 (see Table 1). Findings from one Australian study were included in the overall discussion. No English LCA studies of SUPBs were found in South America or Africa within the scope of this project. Although several African countries have introduced bans on SUPBs (UNEP, 2018), it appears no LCAs have been published on the matter (Bruun, 2019).

Table 1: The seven studies included in this review and meta-analysis.

Authors	Year(s) of publication	Geographic scope
Civancik-Uslu et al.	2019	Spain
COWI A/S & Utrecht University (BIOSPRI)	2018	Europe
Kimmel	2014	USA
Edwards et al.	2011 & 2012	UK
Muthu et al.	2011 & 2012	Hong Kong, China, India
Mattila et al.	2011	Finland
Khoo	2010	Singapore

The reports included in Table 1 are described and assessed in Chapter 3. For each study, the apparent LCA experience of the authors are described, based on findings on the website of institutes, LinkedIn, and Harzing's Publish or Perish, a freeware that collects data on publications and citations from Google Scholar. This meta-analysis considers a number of aspects including the input data, study assumptions, weight of the bags, number of uses, and waste-management scenarios. The review also considered key methodological choices in the modelling of electricity production, recycling and processes with multiple products. In addition to these methodological choices, important assumptions regarding transportation and products substituted by by-products, second-life reuse, etc were considered. A systematic review of the data quality and calculations was not carried out since this would require at least as many resources and detailed information as the original studies. However, the choice of data sources and the errors, if any, that are apparent from the publications were taken into consideration.

In the meta-analysis, the results of the case studies with respect to the key aspects are explained and/or discussed. The explanation is in large parts qualitative or semiquantitative, as the case studies cannot be reconstructed within the frame of this project.

The conclusions of each study based on the findings from the meta-analysis are assessed and discussed. This assessment can include, for example:

- whether the validity of the study is restricted to a specific geographical area,
- whether the goal is to reflect market changes that occur beyond the life cycle of the analysed bag but are induced by the production and use of the bag (consequential perspective – see next chapter for more detail),
- whether the LCA results are a valid estimate of the share of environmental impacts that can be attributed to the different bags (attributional perspective – see next chapter for more detail), and
- whether the conclusions drawn in the study correctly reflect the data and analysis.

Based on the meta-analysis, and on a summary of previous meta-analyses, conclusions regarding the environmental drawbacks and benefits of plastic bags compared to other bags are drawn. Moreover, conclusions on the benefits and limitations of LCA as a tool for environmental comparisons between different shopping bags were derived.

2. Methodological background

2.1 The basics of LCA

Environmental LCA is the calculation and evaluation of the environmentally relevant inputs and outputs and the potential environmental impacts of the life cycle of a product, material or service (ISO, 2006a, 2006b). Environmental inputs and outputs refer to the demand for natural resources, to emissions and to solid waste. The life cycle consists of the technical system of processes and transports used for raw materials extraction, production, use and after use (waste management or recycling).

LCA is well adapted to quantify potential impacts of global or regional scale (e.g climate, acidification, eutrophication and resource use) and represents a powerful tool for environmental comparison of different products, services or technological systems. In addition, LCA brings a holistic perspective into decision-making and has gained acceptance as a decision-making tool in industry, procurement and policy making.

An LCA is divided into four phases. In accordance with the current terminology of the International Organization for Standardization (ISO), the phases are called goal and scope definition, inventory analysis, impact assessment, and interpretation.

Goal and Scope Definition

The first phase consists of defining the LCA’s purpose, as well as the intended audience and application. The purpose determines the type of assessment conducted, either attributional - i.e. only includes the processes that are part of the life cycle under investigation (e.g. the processes that are part of producing an LDPE bag) - or consequential LCA - has a wider perspective and also includes processes that are affected by the supply and use of the product. Functional unit, level of detail, impact categories (e.g. global warming), limitations and assumptions, allocation procedure and system boundaries are also defined and set in accordance with the purpose of the study.

Inventory Analysis

The next phase of an LCA is the inventory analysis. It starts with the construction of the life cycle flow chart and the collection of data for all relevant inputs (energy and material) and outputs (emissions and wastes) along the life cycle. These data are then set in relation to the functional unit defined in the Goal and Scope Definition.

Impact assessment

The third phase of an LCA is the impact assessment, which is divided into classification and characterisation. During the classification, the inventory results are assigned to their respective impact categories e.g. global warming. This is followed by the two-step characterisation, i.e. the inventory results are first multiplied with the equivalence factors of the different impacts and then summed up into the various impacts.

An LCA is generally an iterative process and the impact assessment helps increase the knowledge regarding the environmental importance of inputs and outputs. This knowledge can then be used to collect better data and consequently, improve the inventory analysis.

Interpretation

In the final phase the results are analysed in relation to the goal and scope definition. Conclusions and recommendations with respect to the aim of the assessment are given and the limitations of the results are presented. The conclusions of the LCA should be compatible with the goals and quality of the study.

2.2 Limitations of LCA

The broad system's perspective of LCA comes at the cost of important simplifications in the analysis, compared to the complexity of the actual, real-world system, e.g. an LCA typically does not account for the time and place where emissions occur, or the concentration of hazardous substances in these emissions. The simplifications have different implications, depending on what type of environmental impact is studied:

- The quantification of local impacts and toxicity impacts is severely hampered by a lack of emissions data and by the simplifications necessary to make LCA operational. There are different, competing methods to address the simplifications. As an example, JRC (Joint Research Centre of the European Commission) recently published re-calculated characterisation factors for freshwater ecotoxicity and human toxicity (Saouter et al., 2018).
- The impact on human health of viruses and bacteria is rarely considered in LCA. Such impacts can be important when comparing bags as bags can host infectious bacteria such as *E.coli* (causes diarrhoea). Greene (2011) found, for example, coliform bacteria in half of the bag samples and 12% of the bags carried *E.coli.* As countermeasure they suggest washing plastic bags, which would consume 2 gallons of water plus detergent for the wash and rinse cycles in a standard washing machine.
- Impacts on biodiversity and water resources are difficult to model because they are multifaceted. Many different methods have been suggested. For example, JRC (Sala et al., 2019) recently recommended to use 'user deprivation potential' (impact due to water use) when conducting environmental footprints (EF).
- Methods to quantify littering potential and circularity have been suggested but are not yet widely used.

In addition to these implications, the assumptions, the data sources, the system boundaries and other methodological choices can differ between studies, possibly resulting in contradicting results between LCA studies. Consequently, LCA should not be regarded as a single method but as a complement to other tools and frameworks.

3. Case studies

3.1 Civancik-Uslu et al. (Spain)

3.1.1 Description

Civancik-Uslu et al. (2019) are researchers in Spain and Denmark. They observe that marine littering problem is an important issue for SUPBs and that this is typically not considered in LCAs of bags. To abridge this gap in the methodology, they introduce an indicator for assessing the littering potential on the environment and demonstrate it by adding it to a somewhat old LCA of five different supermarket bags (see Table 2 below), which has been subject to a critical review (Fullana-i-Palmer & Gazulla 2008).

The functional unit in this study is the bags required to bring supermarket goods home to an average Spanish household for a year: 408 single-use bags. The number of bags required is assumed not to vary between the bags depending on the size of the bag but only on the number of times the bag is used (see Civancik-Uslu et al. 2019, Table 2).

The HPDE and LDPE bags were assumed to be produced in Spain and the biodegradable bag in Italy, but the PP bag was presumably produced in China. The paper bag is produced from recycled fibres – probably in Spain, judging from the transport distances (Civancik-Uslu et al. 2019, Table 5). The transport of PP bags from China to Spain is by ship, but all other transports are by truck. The production of HPDE, LDPE and PP is modelled based on data from the Ecoinvent database. Input data on the production of the biodegradable and paper bags were provided by the producers. Civancik-Uslu et al. do not describe what input data were used for modelling of electricity production.

The LCA accounts for the fact that 61% of the population reuse supermarket bags as waste bin liners. It gives the single-use HDPE and biodegradable bags credit for the avoided production of conventional garbage bags that are replaced through this secondary reuse, assuming that almost four supermarket bags are required to replace a single, larger garbage bag.

The LCA does not include a credit for the virgin material production avoided through recycling. More than half of the paper bags, and a smaller share of the HPDE, LDPE and PP bags are recycled after use (Civancik-Uslu et al. 2019, Table 4). However, recycling is modelled through a cut-off approach where the recycling process is allocated to the product using recycled material, but where no environmental burden or credit is assigned to the flow of recyclable materials between life cycles.

Most bags that are not recycled are disposed at controlled landfills with recovery of biogas. A smaller share is incinerated with energy recovery. However, this share varies considerably between the bag types – see Civancik-Uslu et al. 2019, Table 4 for more detail. For the biodegradable bag it is assumed that under landfill it decomposes like paper, while under incineration its emissions are modelled similar to the emissions of a plastic bag. The paper provides no clear statement on whether energy recovery from incineration and landfill gas recovery are modelled with energy credits for the different bags.

Civancik-Uslu et al. (2019) compare the bags in terms of climate impact, acidification, eutrophication, photochemical ozone creation, abiotic resource depletion, primary energy use, water use, and littering potential. Littering potential is quantified by an indicator developed specifically for this paper. It takes into account:

- the number of bags required to meet the functional unit,
- the surface area of each bag,
- the price of the bag, because a cheaper bag is more likely to be left in the environment,
- the weight of the bag, because a lighter bag is more likely to be blown by the wind into, e.g., the ocean, and
- the degradation rate of the bag.

The results of the study indicate that:

- in terms of littering potential, the single-use HDPE bag is almost 30 times worse than the reusable LDPE bag, which in turn is several times worse than the remaining three bag types,
- the HPDE bag is equal to or better than all other bags in terms of acidification, eutrophication, photochemical ozone creation, and water use,
- the climate impact is slightly lower for the LDPE bag, compared to the HDPE bag, but much higher for the other bags,
- the paper bag and the durable PP bag have the greatest impact on the climate but contributes the least to littering potential, while the opposite holds for the LDPE and HDPE bags,
- the acidification is more than double for the PP bag, compared to all other bags,
- the paper bag contributes the most to eutrophication, with the durable PP bag and the biodegradable bag in a tight run on the second place, and
- the water depletion is more than double for the biodegradable bag compared to the paper bag, which still depletes water many times more than the remaining three bags.

Cinvancik-Uslu et al. (2019) conclude that the ranking in term of littering potential is the opposite compared to the conventional LCA results.

3.1.2 Meta-analysis

This LCA includes the avoided emissions from the reduced production of conventional garbage bags that are replaced through secondary reuse of HPDE and biodegradable bags. This means that the study is not limited to the life cycle of the supermarket bags but includes some of the consequences that the use of the bags has on other life cycles. In this sense, the LCA is consequential: the results of the LCA indicates not only the environmental impacts of the life cycle of the HDPE and biodegradable bags, but the broader consequences of using these bags.

On the other hand, the LCA does not account for the consequences on other life cycles of using recycled material or of recycling the bags after use. This mainly affects the paper bags, which are produced from 100% recycled fibres and recycled to a high degree after use. In this sense, the LCA is attributional: its results do not indicate the broader consequences of using paper bags, but merely the environmental impact of the life cycle itself.

The paper bags have a high climate impact according to the LCA results. If they were produced from virgin fibres the climate impact might be much lower Dahlgren & Stripple (2016) or much higher (Kimmel 2014). If the virgin-fibre production has less impact on the climate, it is because it is driven by the energy in the raw material, the pulpwood, while paper recycling requires the use of external fuel that is typically fossil. The eutrophication and photochemical ozone formation of the paper bags would probably be higher, though, if they were produced from virgin fibres.

From a climate perspective, it is beneficial for the paper bags that Civancik-Uslu et al. (2019) do not account for the recycling after use of bags, which is particularly large for the paper bags. If the study included the recycling process and the avoided production of virgin fibres, the paper bag would score better on at least eutrophication and photochemical ozone formation.

Civancik-Uslu et al. (2019) do not make a distinction between the bags based on their size. They implicitly assume that a round of shopping at the supermarket requires the same number of bags, independently of their size. This is probably correct in many cases, most clearly when the purchased goods do not completely fill the smallest of the compared bags. However, in some cases a smaller bag will not be sufficient, and an extra bag will be required. If the bags where compared based on their size, the conventional and the biodegradable bag would come out worse in the comparison. The reusable LDPE bag would be superior to all other bags in all environmental impacts but littering potential. The durable PP and paper bags would also be much more environmentally competitive. The most accurate results are probably somewhere between results based on the assumption that the function of a bag is proportional to its size and results based on the assumption that it is independent of the size.

Compared to other bags, a relatively large share of conventional HDPE bags is assumed to be incinerated. If the actual incineration share is lower for HDPE bags, the climate impact is probably reduced, because more carbon will be stored in the landfills rather than released through incineration.

The results of Civancik-Uslu et al. (2019) indicate that the ranking in terms of littering potential is more or less opposite to the ranking in terms of other environmental aspects. The weight, degradability and the price of the bags were found to be important indicators that influence the probability of the bags becoming litter. Making a bag heavier will reduce its result in the littering potential indicator but increase all other environmental impacts of the bag. The same may be relevant in terms of production of biodegradable material.

Table 2. Summary table for Civancik-Uslu et al. (2019)

		Bags considered in study				
		Single-use HDPE bag	**Reusable LDPE bag**	**Paper bag**	**Biodegradable bag (1 use)**	**PP (20 uses)**
Study Scope	Geographic region	Production- Spain, Italy, China; Use- Spain				
	Life cycle stages	Production, use stage, and end of life				
	End of life assumptions	A generic Spanish waste management scenario (recycling, incineration with energy recovery and landfilling with energy recovery from biogas production). Different share between recycling, incineration and landfilling is assumed for all types of bags. No recycling for biodegradable bag. Conventional HDPE bags and biodegradable bags were also assumed to be reused as bin liners (where the credit for avoided production of conventional garbage bags was considered).				
	Functional unit	The bags required to bring supermarket goods home to an average Spanish household for a year: 408 single-use bags. The number of bags required is assumed not to vary between the bags depending on the size of the bag but only on the number of times the bag is used				
	Material	HDPE (10% recycled)	HDPE (10% recycled)	HDPE (10% recycled)	HDPE (10% recycled)	HDPE (10% recycled)
	Capacity (litres)	13.75	13.75	13.75	13.75	13.75
	Number of uses	1	1	1	1	1
	Weight per functional unit (kg)	3.1	3.1	3.1	3.1	3.1
	Weight per bag (g)	7.62	7.62	7.62	7.62	7.62

Indicators	Climate change	▒	⬜	▓	▒	▒
	Acidification	⬜	▒	▒	▒	▓
	Eutrophication	⬜	⬜	▓	▒	▒
	Photochemical ozone creation (POCP)	⬜	⬜	▒	▒	▓
	Abiotic Resource Depletion (ADP)	▒	▒	▓	⬜	▒
	Water use	⬜	▒	▒	▓	▒
	Littering Potential	▓	▒	▒	▒	⬜
Other comments		• The ranking in terms of littering potential is more or less opposite to ranking of other indicators • Credits for reuse as bin liners for HDPE and degradable bags are included. • While modelling paper from recycled material, benefits for using recycled paper were not included. • The study did not distinguish between the bags depending on their size, assumed that the same quantity of bags is used for shopping (despite their different capacities).				

Performance Key	
⬜	Best
▒	Better
▓	Worse

3.2 BIOSPRI (Europe)

3.2.1 Description

The European Commission (2010, 2012) aims for an innovative EU with a strong bioeconomy. They commissioned the so-called BIOSPRI Study to support research and innovation in this area. Part of this project was an LCA study aiming to provide science-based evidence on the environmental comparison of innovative bio-based products to conventional, petrochemical plastic products. The LCA study was coordinated by the Danish consultancy COWI A/S and Utrecht University (2018) and used input from experienced LCA experts at, for example, the EU Joint Research Center and the University of Geneva. It includes LCAs of seven product groups, one of which was shopping bags.

Three different bags where compared (see Table 3). Since the bags are functionally approximately equivalent, each with a capacity of 20 litre volume and 10 kg weight, they are compared on a 1-1 basis. The functional unit is a single bag. Note that the bags in this study are much heavier than the conventional HDPE and the biodegradable bag assessed by Civancik-Uslu et al. (2019; Section 3.1).

The production of the petrochemical bag, based on oil and natural gas, is modelled using aggregated data from PlasticsEurope (COWI A/S and Utrecht University 2018, p.546). The baseline bag is produced to 30-70% from renewable resources: European maize and potato starch are combined with co-polyesters produced in Europe, to a large extent from fossil fuels. Company-specific data are collected from the largest industrial starch-based bioplastic producers: one that use maize starch and another using potato starch (p. 539). The bio-based LDPE is produced in Brazil from sugarcanes and transported by lorry and ship to Europe, where the bags are produced. This production was modelled to a large extent through data from relevant geographical region, but the polymerisation was modelled based on modified PlasticsEurope data on European fossil-based LDPE production (pp. 544-545).

No reuse as bin-liners is included in this LCA. This might be because such reuse is likely to be the same for all three compared bags.

The waste management of the bags are modelled as an estimated average EU waste management for plastic waste (30% recycling, 39% incineration, 31% landfilling) except that the starch baseline bag is assumed to be composted instead of recycled. Calculations are also made with the theoretical assumption of 100% recycling/composting, incineration, and landfilling.

Allocation is avoided through substitution in several parts of the LCA: it includes the marginal animal feed production displaced by coproducts from starch production, marginal mineral fertilizer production displaced by residues from sugarcane production, marginal heat and electricity production displaced through combustion of bagasse from Brazilian sugarcanes, marginal electricity and heat production displaced by energy recovered at end-of-life of the bags, fossil-based LDPE displaced through LDPE recycling, and the marginal NPK fertilizer displaced through composting of the starch-based plastic.

COWI A/S and Utrecht University (2018, p. 13) calculate results for the 16 impact categories in the Category Rules for Product Environmental Footprint (PEFCR; (European Commission, 2018a). However, they find that the innovative and conventional products cannot be compared on all impacts, due to inconsistencies in input data and other discrepancies. They conclude that a fair comparison can be made only on climate change, terrestrial eutrophication, photochemical ozone formation, particulate matter, and depletion of fossil fuels. However, they compare the bags also in terms of acidification, marine eutrophication and non-renewable energy use (p. 579).

The starch-based baseline bag has similar or more severe impacts than the conventional bag in all five categories (COWI A/S and Utrecht University 2018, p. 579). The bio-based LDPE bag has much lower impact on the climate and requires less fossil fuel and total non-renewable energy, compared to the other bags. On the other hand, the bio-based LDPE bag cause much more acidification, eutrophication, photochemical ozone formation, and emissions of particulate matter. The emissions of particulate matter are at least a factor 30 higher, due to the combustion of sugarcane residues. This practice is phased out in Brazil, which means that the environmental performance of the bio-based LDPE is significantly improving (p. 593). In conclusion, there is no clear environmental ranking between the conventional and the bio-based LDPE bag, but the starch-based bag appears to affect the environment more than the conventional, fossil-based LDPE bag.

3.2.2 Meta-analysis

The BIOSPRI study is reported and discussed in detail, which should allow for transparency and a detailed meta-analysis. However, the complexity of the study and the sheer volume of the report makes it a challenge to identify and assess the key aspects of the study within the frame of the current project. Notably, the LCA does not account for impacts of littering or the problems of microplastics.

We find no information in the report on whether marginal or average data is used to model the supply of electricity etc. that is used in the life cycles. However, the study clearly accounts for consequences beyond the boundaries of the life cycles of the bags. It includes production of animal feed, mineral fertilizer, heat, electricity and virgin LDPE displaced by by-products or recycled substances from the life cycles. This displaced production is modelled using marginal data to the extent possible. This means the study is essentially a consequential study, estimating the consequences for the environment of producing and using the various bags.

In other words, the results and conclusion of the study can be understood as follows:

Replacing conventional LDPE bags with the starch-based bag increases the burdens on the environment, not accounting for impacts of littering and microplastics. Replacing it with a bio-based LDPE bag reduces the impact of society on the climate and the total use of fossil fuel and non-renewable energy in general. On the other hand, it increases the impact of society on acidification, eutrophication, photochemical ozone formation, and the total emissions of particulate matter.

Part of the reason that the starch-based bag has no environmental advantages in the LCA is that it includes fossil-based co-polyesters. The production of these co-polyesters is responsible for a large share of several environmental impacts from the production of starch-based bags (COWI A/S and Utrecht University 2018, p. 551).

However, in terms of climate impact, at least, the consequences of waste management are more important for the total LCA results. The bags are assumed to be recycled or composted (30%), incinerated (39%) or deposited at landfills (31%). At landfills, the starch-based bag affects the climate much more than LDPE bags, because it decomposes to form methane. The recycling of LDPE bags gives a much greater climate benefit than the composting of starch-based bags (COWI A/S and Utrecht University 2018, p. 559), because the recycled LDPE is assumed to replace virgin, fossil-based LDPE while compost residues only replace fertilizers. Finally, LDPE contains more energy than the starch-based material, which means more electricity and heat is recovered at incineration of the LDPE bags. All this is more than enough to compensate for the fact that incineration of the conventional LDPE bag emits more fossil CO_2 compared to the starch-based bag.

The bio-based LDPE bag is five times better than the conventional LDPE bag for the climate (COWI A/S and Utrecht University 2018, p. 579). The difference is big, because all the carbon in the bio-based LDPE is renewable. Of this carbon, 31% is in effect captured from the air and stored in landfills after use of the bags, while 30% is recycled to replace fossil-based LDPE. When indirect land-use changes are accounted for, the climate impact of the bio-based bag increases significantly (p. 591) but is still much smaller than the impacts of the conventional plastic bag.

The bio-based LDPE bag is, much worse than the conventional bag in several other environmental aspects (COWI A/S and Utrecht University 2018, p. 579). This is, at least in part, because of impacts of Brazilian sugarcane production. This contributes to 50% or more of the total cradle-to-gate impacts of the bio-based bag, in terms of particulate matter, acidification, terrestrial and marine eutrophication, and photochemical ozone formation (p. 555). Improvements in this process could, at least in theory, make the bio-based LDPE comparable to or better than the conventional LDPE in most of the environmental aspects discussed here. On the other hand, shifting from conventional LDPE to bio-based LDPE would not solve the problems associated to impacts of littering and microplastics, because the two materials have similar chemical and physical properties.

Table 3. Summary table for BIOSPRI study (COWI A/S and Utrecht University 2018).

		Bags considered in study		
		Conventional LDPE bag	**Biodegradable bag**	**Bio-based LDPE bag**
Study Scope	Geographic region	Production- Europe, Brazil. Use- Europe		
	Life cycle stages	Production, use stage, and end of life	Production, use stage, and end of life	Production, use stage, and end of life
	End of life assumptions	30% recycling, 39% incineration, 31% landfilling	30% composting, 39% incineration, 31% landfilling	30% recycling, 39% incineration, 31% landfilling
	Functional unit	1 single-use all-purpose lightweight plastic carrier bag with the volume of 20 litres and 10 kg weight holding capacity		
	Material	LDPE (100% virgin)	starch and copolyesters	Bio-based LDPE
	Capacity (litres)	20	20	20
	Number of uses	1	1	1
	Weight per functional unit (g)	17.9	22.4	17.9
	Weight per bag (g)	17.9	22.4	17.9
Indicators	Climate change	■	■	□
	Particulate matter	□	□	■
	Photochemical ozone formation	□	□	■
	Acidification	□	▒	■
	Terrestrial eutrophication	□	▒	■
	Marine eutrophication	□	▒	■
	Abiotic depletion	■	■	□
	Non-renewable energy use (NRE)	■	■	□
Other comments		• The results in the table compare bio-based LDPE bags with conventional LDPE bags, cradle-to-grave results excluding land-use changes. When indirect land-use changes are accounted for, the climate impact of the bio-based LDPE bag increases significantly but is still much smaller than the impacts of conventional LDPE bags. • Results change when calculations are made with the theoretical assumption of 100% recycling/composting, incineration, and landfilling.		

Performance Key	
□	Best
▒	Better
■	Worse

3.3 Kimmel (USA)

3.3.1 Description

Robert M. Kimmel is an associate professor in packaging science at Clemson University, who observed that restrictions on carrier bags where implemented in USA despite controversies on what bags are environmentally superior. He conducted an LCA with an aim to provide an objective basis for decisions on bags in the US. The study was reviewed by a panel of three external experts who asserted that the study is ISO compliant (Kimmel, 2014).

This LCA covers six different bags commonly used in the country (see Table 4). Except for the paper bags, these bags are lighter compared to the corresponding bags assessed by Civancik-Uslu et al. (2019), Section 3.1.

A study at Clemson University found that a typical American family use 6.7-9.8 bags for a trip to the grocery store, depending on the size of the bags (Kimmel 2014, pp. 27-29). Edelman Berland found that LDPE bags are reused in average 3.1 times in the US, while non-woven Polypropylene (NWPP) bags on average are reused 14.6 times. The reuse varies greatly between households, and 20% of the population reuse their NWPP bags more than 44 times. Based on these findings, Kimmel made the comparison with four different functional units: 1, 3.1, 14.6 and 44 trips to the grocery store. For all these functional units, a single set of reusable bags was assumed to be sufficient, while a new set of single-use bags where used for each trip.

Polypropylene is assumed to be produced in China and shipped to the US on transoceanic freighter. The other bulk materials are produced in the US and transported by lorry (Kimmel (2014, pp. 34-37). The LCA is based on environmental data from the US-EI2.2 Database. These data are derived from Ecoinvent 2.2, but data on electricity production are replaced by data representing US electricity. The input of recycled HDPE and paper from other products is not assigned any environmental impact.

The LCA results are calculated both with and without the second life. The calculations that include the second life accounts for the production avoided through this reuse, and assumes the avoided product is similar to the reused carrier bag. Based on studies in the US and UK, Kimmel (2014, p. 84-86) assumes that 40% of SUPBs in the US and UK have a second life as trash-can liners etc. He assumes that 22.1% of non-recycled paper bags have a second life.

After use, 8.6% of the SUPBs and 49.5% of the paper bags are recycled (Kimmel 2014, p. 49). Most (82.2%) of the non-recycled bags are deposited at landfills, after possible second-life. The rest (17.8%) is incinerated with recovery of heat and electricity. The recycled material is assumed to replace virgin material of the same type, and the LCA accounts for the avoided production of virgin material (p. 33). It is not clear from the report if the LCA gives credit to the bags for the energy recovered at the waste incinerator or through recovery of landfill gas.

Kimmel (2014) compares the bags in terms of climate impact; terrestrial acidification; freshwater and marine eutrophication; photochemical ozone formation; terrestrial, freshwater, marine and human toxicity; depletion of water and fossil fuel; and cumulative energy demand. The problem associated to impacts of littering is discussed but not included in the LCA.

When each bag is used only once, the plastic single-use bags score the best in most impact categories (Kimmel 2014, p. 109). The plastic bag with 30% recycled content is 0-30% better than the bag produced from 100% virgin raw material, depending on the impact category.

The NWPP bag scores the worst in all categories if used only once. On the other hand, it is the most durable bag. When used the average 14.6 times, the NWPP bag is still much worse than the SUPBs in terms of water depletion, terrestrial ecotoxicity and photochemical ozone formation. However, it is roughly equivalent or superior to them in all other environmental aspects in the study.

The LDPE “wavetop” bag is superior to the NWPP bag, when compared one-to-one. However, when accounting for the fact that the average number of times it is used is just 3.1, it is worse than the SUPBs in all environmental categories and worse than the NWPP bag in all aspects except water depletion and terrestrial ecotoxicity.

The paper bag with just 60% virgin kraft paper does not score better than SUPBs in any environmental aspect covered by the study. The paper bag with 100% recycled fibres scores better than the kraft-paper bag in all environmental aspects, but still worse than the SUPBs in all impacts except acidification, and freshwater and marine toxicity.

In addition, Kimmel (2014, p. 109) calculates the number of times a bag must be used to be environmentally equivalent to the partly recycled plastic single-use bag, i.e., the bag that affects the environment the least, calculated per bag. In terms of GWP:

- the virgin single-use plastic bag must be used 1.1 times; although this difference is small, there is no reason to assume that the virgin single-use plastic bag will be used more times than the partly recycled plastic bag;
- the paper bags must be used 3.7-5.4 times, depending on the content of the paper and on whether the second life is included;
- the LDPE “wavetop” bag must be used 6-9 times, which is significantly more than the US average; and
- the NWPP bag must be used 13-20 times, which is equivalent to or more than the US average.

Kimmel (2014) concludes that if reusable LDPE and NWPP bags are used a sufficient number of times, they have less impact on the environment than the conventional, SUPBs. However, the majority of US consumers do not reuse the reusable bags enough. Kimmel also concludes that paper bags, even with 100% recycled fibres, have significantly higher environmental impacts, compared to the other bags.

3.3.2 Meta-analysis

Kimmel (2014) uses average data. However, he applies the avoided burdens approach in all calculations when they are recycled after use (p. 33) and in the second part of the study- where bags are reused in a second life. This makes the study a mix of attributional and consequential LCA. The results are not really an estimate of the share of global environmental impacts that belongs to the bags, nor an estimate of the consequences of using the bags.

The base case scenario did not include the “second life” of the bags, however it was included in the second part of the study. Assuming that SUPBs replace similar bags in their second life is optimistic. Conventional bin liners are typically lighter than carrier bags. On the other hand, the assumption that 40% of the SUPBs are reused is on the low end of the findings from previous studies cited by Kimmel. The assumption that the share of second life of paper bags is 22.1% is uncertain and might also be optimistic. Overall, the modelling of the second life is uncertain and might contribute to underestimating the environmental impacts of paper bags.

The use of recycled materials in the bags seems to be modelled using a cut-off approach, which means the recycled material in the bags is not assigned any environmental impact. However, recycling of bags after use is modelled using the avoided-burdens approach: material recycled after use in the bags is credited by the avoided virgin production. Such modelling of recycling means double-counting of the environmental gain of recycling. This is most clear and important in the LCA of the recycled paper bag, which contains 100% recycled fibres and is recycled to 49.5% after use. When the recycled input carries no part of the virgin production and the recycled output is credited for avoided virgin fibre production, the net total virgin fibre production in the LCA is nearly -50%. This is an illustrative consequence of mixing an attributional method (cut-off) and a consequential method (avoided burdens). Results assigning -50% of virgin production to the paper bag do not reflect a share of global environmental impacts, nor an estimate of the consequences of using the bags. With the data used in this study, the results for the paper bags would be even worse than they are, if the LCA used a cut-off or an avoided-burdens approach consistently.

Despite the large credit for recycling after use, the waste processing of paper bags has a large impact on the climate (Kimmel 2014, p. 57). This is probably because most non-recycled bags are deposited at landfills, where the paper bags generate methane as they decompose.

The results of this study indicate that paper bags in the US are much worse for the environment, compared to the other bags. Providing that average reuse rates for LDPE bags is 3.1 times, and 14.1 times for NWPP, the LDPE wavetop bag is significantly worse than the SUPBs for the average US consumer. The durable NWPP bag is worse than or roughly equivalent to the SUPBs, depending on what environmental impacts are considered important. These conclusions disregard the impacts of littering and microplastics, since they are not included in the LCA.

Table 4. Summary table for Kimmel (2014)

		Bags considered in study					
		Conventional single-use HDPE bag	**Partly recycled single-use HDPE bag**	**Single-use Paper bag (partly virgin)**	**Single-use Paper bag (100% recycled)**	**Reusable LDPE bags**	**Reusable NWPP bags**
Study Scope	Geographic region	Production- North America, Europe, China, Use- USA					
	Life cycle stages	Production, use stage, and end of life					
	End of life assumptions	recycled (8.6%), incinerated (16.3%), landfilled (75.1%)		recycled (49.5%), incinerated (9%), landfilled (41.5%)		incinerated (17.8%), landfilled (82.2%)	
	Functional unit	Bags used by U.S. consumers to transport the shopping items for one trip (52 items) from the grocery store to the consumer's home in 2012.Four different scenarios of numbers of trips were analysed: 1, 3.1, 14.6 and 44 trips to the grocery store. For all these functional units, a single set of reusable bags was assumed to be sufficient, while a new set of single-use bags where used for each trip.					
	Material	Virgin HDPE	70% virgin HDPE; 30% recycled HDPE	60% kraft paper; 40% recycled paper	Recycled paper (100%)	LDPE	Non-woven PP ; LDPE insert
	Capacity (litres)	did not specify the capacity of each bag, but considered the number of bags used by a typical American family for a trip to the grocery store: Retail plastic bags (9.8 bags), paper (8.4), LDPE (8.3), NWPP (6.7).					
	Number of uses	1	1	1	1	1-44	1-44
	Weight per functional unit (g)	61 – 2684	61 – 2684	457 – 20116	457 – 20116	296	622
	Weight per bag (g)	6.2	6.2	54.4	54.4	35.6	Bag: 60.8; LDPE insert: 32
Indicators	Climate change	▒	▒	▓	▒	░	▒
	Water depletion	░	░	▓	▒	░	▒
	Cumulative Energy Demand	▒	▒	▓	▒	░	▒
	Terrestrial acidification	▒	▒	▓	▒	░	▒
	Freshwater eutrophication	░	░	▓	▒	░	░
	Marine eutrophication	▒	▒	▓	▓	░	▒
	Human toxicity	▒	▒	▓	▒	░	▒
	Terrestrial ecotoxicity	░	░	▓	▒	░	▒
	Freshwater and marine ecotoxicity	▒	▒	▓	▒	░	▒
	Fossil Fuel Depletion	▒	▒	▓	▓	░	▒
	Photochemical oxidant formation	░	░	▓	▒	░	▒

Other comments	• The results in this table are shown for the functional unit of 14.6 trips (i.e. it was assumed that the reusable bags (LDPE and NWPP) are reused 14.5 times), and base case scenario (i.e. where second life is not considered). • Results change depending on different scenarios that have been tested in the study (numbers of trips, secondary use). • The reusable LDPE and NWPP bags will have lower average impacts if they are reused for a sufficient number (6-9 times for the LDPE “wavetop” bag and 13-20 times for the NWPP bag). The paper bags must be used 3.7-5.4 times, depending on the content of the paper and on whether the second life is included.

Performance Key	
░	Best
▒	Better
▓	Worse

3.4 Edwards et al. (UK)

3.4.1 Description

A debate on the environmental impacts of carrier bags arose in the UK at the beginning of the century, as part of the debate on the impacts of food packaging. The number of lightweight carrier bags were cut almost in half from the year 2006 to 2009, but the UK Environment still considered the bags an important issue. They observed that many LCAs had been made to compare different bags, but that these were not fully applicable to the British context. For this reason, they commissioned an LCA to compared different types of bags used in British supermarkets (Table 5), with an aim to help both authorities and supermarkets reduce the environmental impacts of carrier bags. The difference in weight between the durable bags and the conventional, single-use plastic bag is somewhat less in this study, compared to Civancik-Uslu et al. (2019; Section 3.1).

The study was carried through by Edwards and Fry (2011), two consultants with significant previous experience from LCA. The study was informed and assisted by an Advisory Boards with 17 representatives from British authorities and the British Retail Consortium, and by a Stakeholder Consultation Group. A panel of three experts performed an external review of the study.

The functional unit is the number of bags required to carry one month’s shopping by the average supermarket shopper in the UK. The cotton bag is significantly larger than the other bags. Edwards and Fry (2011, p. 17) use the volume of the bags to calculate the number of bags needed to meet the functional unit. They found that the functional unit corresponds to, 46 usages of durable cotton bags or 82 plastic single-use bags. They do not have data on how many times different bags were used, but initially assume that each bag is used only once. Then they calculate how many times a paper bag or a reusable bag must be used before it affects the climate less than the conventional HDPE bag.

The HDPE, PP and cotton bags in this study, and part of the LDPE bags, are produced in Far East Asia and transported to the UK. Part of the LDPE bags are produced in Turkey. The biopolymer bag is produced in Norway. The paper bags are assumed to be produced somewhere in Europe from European paper fibres (Edwards and Fry 2011, p. 27).

Data on the production of the cotton bag and of fossil plastic raw materials (HDPE, LDPE and PP) are from Ecoinvent. The data on fossil plastics originate from PlasticsEurope. Data on the production of the starch-polyester blend and the biopolymer bag is supplied by the producer. Data on paper and paper bag production are developed by the Swedish STFI-Packforsk, based on European data from CEPI Eurokraft and Eurosac.

Production of the bags from raw materials in most cases requires electricity and, in the case of LDPE and PP bags, also heat. Edwards and Fry (2011, p. 27) assume natural gas to supply heat to the production of bags from LDPE, while supplier information indicates that heavy fuel oil is used to produce the PP bags. The supply of electricity to all processes is modelled using national average data on electricity production.

Edwards and Fry (2011, pp. 30-31) account for the fact that part of the lightweight carrier bags are reused as kitchen bin liners, based on information from WRAP (2005). They do not, however, account for other types of reuse (bin liners in other rooms, direct use for getting rid of rubbish, storage at home, etc.).

At the end of their use, most of the bags (86%) are assumed to be landfilled, with the remaining 14% being incinerated (Edwards and Fry 2011, p.31). The biopolymer and paper bags are assumed to degrade in landfills and contribute to methane emissions. However, the degradable bag is not assumed to contribute to these emissions (Edwards and Parker, p. 9). This is consistent with Roy et al. (2011) who state that an oxo-degradable bag breaks up into very small pieces but might not degrade chemically in a realistic time frame. Jakubowicz et al. (2011), in contrast, found that oxo-degradable plastics to 91% is converted to CO_2 within two years in soil.

The possibility of recycling or composting the bags is included in a sensitivity analysis. Degradable polymers can cause problems in the recycling process (ibid., p.48). For this reason, the recycling option is not included for the degradable plastic bag. However, the study does not account for problems occurring because degradable polymer bags inadvertently end up in the recycling stream.

The boundaries of the LCA are expanded to account for avoided production of:

- conventional bin liners, when the plastic bags are reused for lining kitchen waste-bins,
- virgin material, when materials from the bag life cycles are recycled, and
- electricity, when energy is recovered from materials through incineration or extraction of landfill gas.

Edwards and Fry (2011) compare the bags in terms of climate impacts, acidification, eutrophication, photo-oxidant formation, human toxicity, and terrestrial and aquatic (marine and freshwater) ecotoxicity. Their results indicate that (ibid. Chapter 5 and Figure 7.1):

- the environmental difference between a conventional and a degradable HDPE bag is small, with the conventional HDPE bag a little bit better in all aspects,
- the biopolymer bag is worse than the HDPE bags in all environmental aspects, except for abiotic depletion where it is almost as bad,
- a paper bag must be reused four times more than the HDPE bags for shopping to have a lower climate impact; in this case the paper bag contributes much less to abiotic depletion and marine ecotoxicity, but is much worse than the HDPE bags in terms of human toxicity and terrestrial ecotoxicity,
- a heavy-duty LDPE bag must be reused five times more than the HDPE bags to have a lower climate impact; in this case the LDPE bag contributes much less to acidification and aquatic ecotoxicity,
- a non-woven PP bag must be reused 14 times more than the HDPE bags to have a lower climate impact; in this case the PP bag contributes less to acidification and aquatic ecotoxicity, but more to terrestrial ecotoxicity, and
- a cotton bag must be used 173 times more than the HDPE bags to have a lower climate impact; if this can be achieved, the cotton bag contributes less to abiotic depletion, but much more to eutrophication and toxicity, compared to the HDPE bags.

Edwards and Fry (2011, Section 7.1) compared their results to three previous studies and find, for example, that the climate impact of the biopolymer bag varies greatly between studies. The two studies that included paper bags agree with the results of Edward and Fry in that the climate impact of a single paper bag are several times the impact of a single conventional HDPE bag.

They observe that the LCA results are sensitive to the amount of material in the bag, the rate of reuse in shopping and secondary reuse at home, and the waste management.

Symphony Environmental has a stake in the debate on bags since it is a producer of a pro-degradant additive that can be used in degradable bags. They found that Edwards and Fry (2011) did not account for the environmental aspect that degradable bags are designed to address: the impacts of littering. They asked Edwards and Parker (2012) at the consultancy Intertek to expand the LCA on lightweight carrier bags: conventional HPDE, oxo-degradable HDPE and biopolymer bags (Table 6). In addition to the environmental impacts of the original study, the expanded study includes ozone depletion and litter aesthetics. The latter is quantified by multiplying the area of the litter and the time it takes for it to break up to fragments too small for the naked eye to see.

The study has similarities to the original study, but the functional unit is 1 bag, the weight of the two HDPE bags is assumed to be identical, and the Italian biopolymer is assumed to be converted to bags in China.

Also, the study does not include the secondary reuse in the household and the avoided production of bin liners, nor does it include the recycling option and the associated avoided production of virgin material.

Edwards and Parker (2012, pp.23-24) estimate 0.75% of the bags to end up as litter. This share is assumed to be the same for degradable bags and conventional bags, based on findings from Thomas et al. (2010). The degradable bag is assumed to degrade with oxygen to form CO_2 in six months. The biopolymer bag is assumed to degrade with water in a year, and the conventional bag is assumed to degrade with oxygen over many decades.

Most of the bags still end up at landfills. Here, Edwards and Parker (2012, p.24) assume that all degradation is anaerobic, and that the oxo-degradable HPDE bag does not degrade because of the lack of oxygen. This assumption is likely to be an important simplification of reality: it takes a while for lack of oxygen to occur in the landfill, and if the bag degrades in six months it might have completely degraded before then, forming CO_2 that contributes to climate change.

The results of this second study indicate almost exactly the same environmental impacts for the oxo-degradable and conventional HPDE bags, except for the impacts of littering, where the degradable bag is much better. The biopolymer bag scores well in terms of littering potential, but worse than the HDPE bags in all other aspects.

3.4.2 Meta-analysis

The studies by Edwards et al. are quite transparent and can be analysed in some detail. Edwards and Fry (2011) mix elements from attributional LCA (e.g., national average electricity data) and consequential LCA (credit for avoided production of bin liners, virgin material, and electricity). For most of the bags the average data can be considered proxies for marginal data. The LCA results can then be regarded as estimates of how the environment is affected by the production and use of the bag.

The exception is the biopolymer bag, which Edwards and Fry (2011) assume is produced in Norway. Norwegian average electricity is dominated by hydropower, which is a very poor proxy for the consequences of using electricity in Norway. This is instead likely to affect the trade of electricity and the production of electricity in other countries, with quite different environmental impacts compared to hydropower. For this reason, the results of the LCA cannot be interpreted as an estimate of how the environment is affected by the production and use of the biopolymer bag. In fact, their LCA of the biopolymer bag does not respond to a well-defined question.

Edwards and Parker (2012) do not include avoided production and bin liners. The environmental benefits of energy recovery from the waste are small, because only a small fraction of the bags are incinerated. This means the study can be interpreted as essentially an attributional LCA that estimates how much of the global environmental impacts belong to a shopping bag.

Edwards and Fry (2011) study assumes that all bags are filled to their limit, given by their volume. This might be correct in some cases but not in others, for example not when the consumer buys few items or finds that a full bag is too heavy to carry. In these cases, a smaller bag is a good substitute for a large bag. Since most bags have similar volume (ibid., Table 4), this only has a significant effect on the LCA results for the cotton bags. If the cotton bag is assumed to, in practice, hold the same goods as any other bag, the LCA results for the cotton bag is almost 50% higher.

The biopolymer and paper bags are produced in Europe, which means they are not transported from the Far East. On the other hand, they are transported on lorries between countries in Europe. The results of Edwards and Fry (2011, Chapter 5) indicate that the climate impacts of the transports in the life cycle of 1 kg biopolymer or paper bags affects the climate more than the total transports of 1 kg conventional HDPE bags produced in China. It seems the shipment of bags from China to the UK has little impact compared to other parts of the life cycle. Long-distance road transport between European countries have a greater environmental impact.

Edwards and Fry (2011, pp. 30-31) estimate, based on WRAP (2005), that 76% of lightweight carrier bags are reused for another purpose after use in shopping. They assume (based on the same source) that 40.3% (53% of 76%) are reused as kitchen bin liners and account for the replaced conventional bin liners. However, they do not account for the secondary reuse of the remaining 76-40.3=35.7% of the lightweight bags (for getting rid of garbage, storage, etc.). This means that the environmental benefit of the secondary reuse of lightweight bags is underestimated. Accounting for this benefit would reduce the total LCA results of all lightweight bags: for example, if 76% of the HPDE bags replace a conventional bin liner, their net total climate impact would be reduced by approximately 25%.

The weight of the degradable and biopolymer bags is possibly too high in the calculations of Edwards and Fry (2011). Supermarket data indicate that the average degradable HDPE bag weighs 7.72 g (ibid., Table B.4.2), but in the LCA the weight seems to be 8.27 g, which is slightly more than the 8.12 g assumed for the conventional HDPE bag (ibid., Table 3.1). If this is correct, the environmental impacts of the degradable bag are overestimated by 7%, which means the environmental impact of the average degradable bag is almost the same as for the conventional HDPE bag. This is also the conclusion of Edwards and Parker (2012), who assume the two HDPE bags to have the same weight.

The biopolymer bag weighs 15.8 g according to supplier data (Edwards and Fry 2011, Table B.4.2) but 16.49 g in the LCA (ibid. Table 3.1). This exaggerates the environmental impacts of the biopolymer bag slightly but does not affect any conclusions. In the complementary study, Edwards and Parker (2012) assumes the biopolymer bag to weigh only 10.68 g. If this weight were used in the first study, all impacts of the biopolymer bag would be 35% lower. It would score better than the HDPE bags in abiotic depletion and be comparable in terms of acidification and photo-oxidant formation. It would still be worse than the HDPE bags in other aspects, though.

On the other hand, the biopolymer bag benefits from the use of national average electricity, since it is produced in Norway where electricity production is dominated by hydropower. The results of Edwards and Fry (2011, Figure 5.5) indicate that the production of bags from the biopolymer hardly has any environmental impact. However, this production process requires more electricity per kg of bag than the production of bags from other plastics (HDPE, LDPE and PP; ibid. Table 4.2), and the impact of the Chinese electricity used for production of HDPE bags is important for their total environmental profile. If the biopolymer bags where produced using similar electricity, like Edwards and Parker (2012) assume, the total climate impact of the biopolymer bag would increase by approximately 30%. Other impacts would also increase significantly, making the biopolymer bag worse than the HDPE bags in all or nearly all impact categories, as suggested by the results from Edwards and Parker. This demonstrates that the location of a production process can be important for the total results in an attributional LCA based on national average electricity data. In other words, if the task of the LCA is to estimate what part of the global environmental impacts that belongs to a bag, the location of the production of the bag can be important – not so much because of the transport distance but because of the electricity mix in the country.

The study assumes that degradable bags in landfills do not degrade at all because of lack of oxygen in the landfill. If they have time to degrade partly or fully in the initial, aerobic phase of the landfill, they will contribute to the formation of micro plastics and/or fossil CO_2 emission, depending on how far it degrades. If the degradable bag degrades fully to CO_2 these emissions will affect the climate as much as the rest of the life cycle. The degradable bag will then be worse for the climate than the conventional HDPE bag and a light (10.7 g) biopolymer bag but still better than the heavier (16.5 g) biopolymer bag and the paper bag.

In combination these comments suggest that, in a UK context, the HDPE bags are even more environmentally competitive than the LCA results indicate. The degradable bag is superior to the conventional HDPE bag in terms of visible littering potential but cannot be recycled, can cause problems in the recycling of other plastics, and also contributes more to the formation of microplastics and/or climate change. In a country with more waste incineration, the HDPE bags would suffer from additional emissions of fossil CO_2 etc. from the incineration.

Table 5. Summary table for Edwards & Fry (2011)

		Bags considered in study						
		HDPE bag	**Degradable HDPE bag**	**Biopolymer bag**	**Paper bag**	**LDPE bag**	**NWPP bag**	**Cotton bag**
Study Scope	Geographic region	Production- East Asia, Europe, Use- UK						
	Life cycle stages	Production, use stage, and end of life						
	End of life assumptions	86 % of all bags were assumed to be landfilled and 14 % incinerated. The possibility of recycling and composting is included in sensitivity analysis						
	Functional unit	Carrying one month's shopping (483 items) from the supermarket to home in the UK in 2006/07						
	Material	HDPE	HDPE with prodegradant additive	Starch and polyester	Paper	LDPE	PP	Cotton
	Capacity (litres)	19.1	19.1	19.1	20.1	19.1	19.75	28.65
	Number of uses	1	1	1	1-4	1-5	1-14	1-173
	Weight per functional unit (kg)	0.67	0.68	1.35	3.59	2.12	7.66	8.35
	Weight per bag (g)	8.12	8.27	16.49	55.2	34.94	115.83	183.11
Indicators	Climate change	▨	□	■	□	▨	▨	▨
	Abiotic depletion	▨	■	▨	□	▨	■	▨
	Acidification	▨	▨	■	▨	□	▨	■
	Eutrophication	□	□	■	▨	□	▨	▨
	Human toxicity	□	□	■	▨	□	□	□
	Fresh water aquatic ecotoxicity	▨	▨	■	□	□	□	▨
	Marine aquatic ecotoxicity	▨	▨	■	□	□	▨	■
	Terrestrial ecotoxicity	□	□	▨	▨	□	▨	■
	Photochemical oxidation	▨	▨	■	▨	□	▨	▨
Other comments		• The results are shown for the following number of uses: Conventional HDPE bag, Degradable plastic bag, Biopolymer bag- 1 use, Paper bag- 4 uses, LDPE "Bag for life"- 5 times, Non-woven PP bag- 14 times, Cotton bag- 173 times. Other numbers of uses are tested in the study. • The study accounts for the fact that part of the lightweight carrier bags are reused as kitchen bin liners. • The LCA results are sensitive to the amount of material in the bag, the rate of reuse in shopping and secondary reuse at home, and the waste management.						

Performance Key	
□	Best
▨	Better
■	Worse

Table 6. Summary table for Edwards & Parker (2012)

		Bags considered in study		
		Conventional HDPE bag	**Oxy-degradable plastic bag**	**Bio-based carrier bag**
Study Scope	Geographic region	Production- Italy (bio-based polymer), China, Use- UK		
	Life cycle stages	Production, use stage, and end of life		
	End of life assumptions	‘current’ situation which includes landfill, incineration and litter, based on UK statistics		
	Functional unit	“The production, use and disposal of a single conventional light weight bag and alternatives of the same capacity		
	Material	HDPE	HDPE with prodegradant additive	Starch and polyester
	Capacity (litres)	19.1	19.1	19.1
	Weight per bag (g)	8.17	8.17	10.62
Indicators	Global Warming Potential	⬜	⬜	⬛
	Littering Potential	⬛	⬜	⬜
	Abiotic depletion	⬜	⬜	⬛
	Acidification	⬜	⬜	⬛
	Eutrophication	⬜	⬜	⬛
	Ozone layer depletion	⬜	⬜	⬛
	Human toxicity	⬜	⬜	⬛
	Fresh water aquatic ecotoxicity	⬜	⬜	⬛
	Marine aquatic acotoxicity	⬜	⬜	⬛
	Terrestrial ecotoxicity	⬜	⬜	⬛
	Photochemical oxidation	⬜	⬜	⬛
Other comments		• The study found almost exactly the same environmental impacts for the oxo-degradable and conventional HPDE bags, except for littering potential, where the degradable bag is much better. • Recycling, composting, reuse have been excluded. • It was assumed that the impact of oxo-biodegradable plastics in landfill is the same as that of conventional plastics, with no anaerobic degradation.		

Performance Key	
⬜	Best
▒	Better
⬛	Worse

3.5 Muthu et al. (China, Hong Kong and India)

3.5.1 Description

Muthu et al. (Muthu, Li, Hu, & Mok, 2011; Muthu, Li, Hu, Mok, & Ding, 2012) is a group of textile researchers at universities in Hong Kong and Shanghai - the first author was a PhD student at the time of the study, and it seems none of the co-authors had any significant previous LCA experience.

Muthu et al. (2011) observe that some of the many LCAs on shopping bags are based on assumptions regarding the waste management system. Their study aims to compare shopping bags based on real data on waste management collected through a consumer questionnaire survey in mainland China, Hong Kong and India. They compare the climate impact of two single-use and two durable bags (see Table 7). The functional unit is the annual number of bags used for grocery shopping by an average person. In China and Hong Kong, they estimate the number of single-use bags to be 1095 bags per person and year. For India the estimate is 150 bags per person and year. Even the number for India is higher than the estimate made by Mattila et al. (2011) for an average Finnish household: 100 bags per year.

Muthu et al. (2011) assume, based on previous literature, that a durable PP bag replaces 100 single-use bags (plastic and paper), while a durable cotton bag replaces 50 single-use bags (paper and plastic). Most other methodological choices and assumptions in the study are not presented in the paper.

The initial carbon footprint results indicate that the durable PP bag is by far the best bag for the climate. SUPBs and cotton bags have comparable climate impact, while the single-use paper bag is by far the worst. Muthu et al. (2011) state that paper production requires “a tremendous amount of energy from fossil fuels, electricity, chemicals, etc.”.

Muthu et al. (2011) then modify the carbon footprint using results from the consumer survey that indicate the rate of recycling, reuse and landfilling of each type of bag in China, Hong Kong and India, respectively. For example, the survey results indicate that the reuse rate of the durable PP bag is 78% in China 69%, in Hong Kong, and 55% in India. The modified results are all significantly lower than the initial carbon footprint results, presumably because of the reuse and recycling of the bags. The reuse rate is much higher for the cotton bag (73-80%) than for the plastic single-use bag (42-55%), and the adjusted results also indicate that the cotton bag is better for the climate. The durable PP bag is still by far the best, and the paper bag is still by far the worst.

Muthu et al. (2012) expand the environmental comparison of single-use paper and plastic bags by including acidification/eutrophication, ecotoxicity, radiation, carcinogenic emissions, respiratory organics, respiratory inorganics, impacts on the ozone layer, land use, and use of minerals and fossil fuel. They also aggregate all impacts into a single indicator using the Ecoindicator 99 approach. They modify the initial LCA results using three different scenarios for the reuse and recycle rates. Bags that are not reused nor recycled are in this study deposited at landfills.

According to both the initial and the modified LCA results, the plastic bag is environmentally superior to the paper bag. It has less than 40% of the impact of paper bags in all environmental impacts in the study, even in the use of fossil fuels.

When aggregated with the Ecoindicator 99 approach, the LCA results are dominated by emissions of respiratory inorganics, with some contribution also from carcinogenics and the use of fossil fuel. Muthu et al. (2012) observe that recycling and, in particular, reuse reduce the environmental impacts of both paper and plastic bags.

3.5.2 Meta-analysis

Since Muthu et al. do not present their choice of data, system boundaries, etc., it cannot be judged whether the study should be considered an attributional or consequential LCA.

The durable bags are better than the single-use bags according to the results from Muthu et al. (2011). This is presumably because much less material is used per functional unit (see Table 7). The best bag for the climate, by far, is the durable PP bag. The amount of material is also, by far, the smallest for the durable PP bag, because it is assumed to replace 100 single-use bags. However, the assumption that a single durable bag replaces 100 (PP) or 50 (cotton) single-use bags seems to be contradicted by the results from the survey where the consumers state they reuse only 55-78% of the PP bags and 73-80% of the cotton bags (Muthu et al. 2011, Table 3). The survey results indicate that an average durable PP bag is used only 2-5 times, depending on country, while a cotton bag is used 4-5 times.

The assumption that a durable bag replaces 50 or 100 single-use bags (plastic and paper) is even more inconsistent with the data from the consumer survey when one considers that also single-use bags are re-used - at a rate of 46-55% for plastic bags and 28-42% for paper bags. Based on these data it seems that a durable PP bag replaces only 1-3 single-use bags, while a cotton bag replaces 2-4 single-use bags.

Muthu et al. (2011) use the survey results to adjust their initial carbon footprint results downwards. If consumers were to use a durable bag five times or less, instead of 50-100 times or more, the initial results should have been adjusted upwards drastically. It seems they have double-counted the reuse of the durable bag, accounting for first both the assumed and the actual reuse rate. Such an important error might be plausible because of the little experience in LCA.

With the interpretation of the survey data, the climate impacts of both durable bags are worse for the climate compared to both single-use bags. They are not reused sufficient number of times to be competitive from a climate perspective.

Table 7. Summary table for Muthu et al. 2011

		Bags considered in study			
		Single use plastic bag	**Paper bag**	**NWPP bag**	**Woven durable bag**
Study Scope	Geographic region	Hong Kong, China, India			
	Life cycle stages	production, use, disposal			
	End of life assumptions	combination of recycling, re-use and landfill; shares of options depend on country			
	Functional unit	“number of shopping bags used for grocery shopping per year by an average Chinese/Indian/HK resident”			
	Material	unspecified polyethylene (PE)	paper	PP	cotton
	Capacity (litres)	N/A	N/A	N/A	N/A
	Number of uses	N/A	N/A	N/A	N/A
	Weight per functional unit (g)	6,570	46,650	720	2,750
	Weight per bag (g)	6	42.6	65.6	125.4
Indicators	Climate change	░	▓	⬜	░
Other comments		• The consumption of material influences the results; a low material consumption for durable bags has a lowering effect on their environmental impact. • High replacement rate lower the environmental impact of the bags (assumption durable PP replaces 100 single use bags, cotton bags replace 50 single use plastic bags).			

Performance Key	
⬜	Best
░	Better
▓	Worse

3.6 Mattila et al. (Finland)

3.6.1 Description

Mattila et al. (Mattila et al., 2011; Mattila et al., 2009) are environmental researchers in Finland – at least a couple of them with previous experience from studies on LCA methodology and applications in, for example, wastepaper management. They observe that previous LCAs comparing different bags have reached contradicting conclusions. To better support decision-making, they carry through a comparative LCA with a systematic sensitivity and uncertainty analysis. The study is partly funded by competing bag producers that also supplies data to the study. This vouches for a balanced LCA.

The five bags compared (Table 8) are commonly sold in Finnish grocery stores, and the bags are assumed to be used in Finland. The SUPBs are heavier than in other LCAs.

The functional unit is the bags required to carry groceries for a year to an average Finnish household. This is translated into 100 single-use bags, based on how many bags were actually bought in Finland in the year 2007. This is much lower than the numbers estimated by Civancik-Uslu et al. (2019): 408 single-use bags per year. It is also lower than the numbers per person estimated by Muthu et al. (2011) for China (1095 per year) and India (150 per year). The size of the conventional plastic bag is likely to vary from country to country. Part of the difference in number of bags can also be explained if the Finnish single-use bags are used for shopping more than once. The number of times a bag is used does not enter the equation of Mattila et al. 2011) since they know the number of bags required for carrying the groceries from statistics.

All single-use bags in the study are considered functionally equivalent, because they all have a capacity of over 30 liters and 20 kg which is more than consumers would comfortably carry (Mattila et al. 2011, p. 219). Mattila et al. assume a cotton bag to replace 50-150 single-use bags, depending on the durability of the bag and the consumer behavior, and that the annual 100 single-use bags correspond to 0.5-1.5 cotton bags. In comparison, Muthu et al. (2011) assumes a cotton bag replaces 50 single-use bags, and Kimmel (2014) quotes that the number of times a durable bag is used in the US is much lower.

After use for transporting groceries, most SUPBs in Finland are used as waste-bin liners in the households. The biodegradable bags can instead be used as composting bags. The single-use bags are credited with the avoided production of conventional PE bin liners and composting bags. Paper bags are instead recycled to a high degree and credited with the avoided production of thermomechanical pulp. All bags are credited with the production of electricity and heat that is avoided when energy in the bags is recovered in waste incineration.

The production of Finnish bags and paper recycling was modelled with process data from Finnish industry, but the production of polyethylene, cotton and modified starch is modelled with data from Ecoinvent 2.0.

The waste management and the energy supplied to the life cycle are modelled based on average Finnish data. Alternative waste scenarios were created as part of the uncertainty analysis. Monte Carlo simulations were made to address the parameter uncertainty and variability not only in the number of cotton bags and the weight of each cotton bag (see above), but also in 22 other variables.

The results indicate that use of biodegradable bags in Finland is very likely to have the greatest impact on the climate, and the recycled PE (RPE) bags probably affect the climate the least (Mattila et al. 2011, Table 2). The production and use of RPE bags can even be beneficial to the climate, because the greenhouse gas (GHG) emissions avoided through reduced use of bin liners, composing bags, etc. can be larger than the GHG actually emitted in the life cycle of the RPE bags.

Paper bags are on average better than conventional PE bags. However, the plastic bag is likely to be better for the climate when it replaces multiple or heavy bin liners, the electricity used in avoided thermomechanical pulp production has a low share of fossil fuel, the recycling rate of paper is low, and paper deposited at landfills degrades to a high degree.

Cotton bags are on average slightly better for the climate, compared to paper bags. However, the paper bag is superior if it is recycled to a high degree, the avoided electricity production has large emissions, and/or the methane generated in landfills are collected to a high degree.

Most plastic and cotton bags used in Finland ended up at landfills when the study was made (Mattila et al. 2011, p. 220). This also holds for the share of paper bags that are not recycled. With another waste-management system, the ranking order of bags can change in a complex way. If the waste management system is dominated by incineration or by efficient sorting and recovery of waste, the conventional PE bag in many cases is the worst for the climate, while the cotton or paper bag is likely to be the best option (Mattila et al. 2011, Table 3). If the waste-management is dominated by incineration without energy recovery, or with recovered energy that replaces carbon-neutral energy sources, the biodegradable bag might even turn out to be the best for the climate.

Mattila et al. (2011, pp. 225-226) observe that the paper bag has less climate impacts in their LCA compared to some other studies. They explain that this is probably because of “the high fraction of wood energy in the Scandinavian paper industry and the use of integrated recycling and paper production facilities”.

Mattila et al. also observe that the climate impact of bags is small: 1 km of car driving corresponds to approximately six single-use shopping bags. Because of the overlapping results and small overall climate impact, they conclude that the climate impact is not a good reason for limiting the use of specific bags.

3.6.2 Meta-analysis

The study of Mattila et al. (2011) includes elements of both attributional and consequential LCA (cf. Section 2.2). The use of average data is consistent with ALCA. On the other hand, they give credit for avoided production of bin liners, composting bags, thermomechanical paper, and electricity and heat replaced through waste incineration. Modelling such substitution is more consistent with CLCA. The substitution is important for the total results: it affects the ranking order between the bags and can even lead to negative net total results, indicating that the production and use of the bag is beneficial for the climate.

If the average data are considered as proxies for the uncertain marginal effects on the energy and waste-management systems, the study can be regarded as a CLCA. In other words, the results are an estimate of how the global GHG emissions would be affected by the use of the bags. Negative net results in this context can occur because recycled PE is used to produce a bag that substitutes a waste liner produced from virgin plastics, thus reducing global GHG emissions. It can also occur because global GHG emissions are reduced when a paper bag is incinerated, and the recovered electricity and heat replace energy from fossil sources.

The bag produced from recycled PE is likely to have relatively little climate impact when used in Finland. This is partly because Finnish waste management was dominated by landfills when the LCA was made. Most of the carbon in conventional plastic bags is likely to be stored in the landfill for more than 100 years, which is the time horizon of the study. The biodegradable plastic bag and the paper bag, in contrast, will degrade to a high degree, forming methane which is a powerful GHG.

The recycled PE bag affects the climate much less than the conventional PE bag (Mattila et al. 2011, Table 3). This indicates that the study associates no emissions to the use of recycled PE. However, recycled PE cannot exist without the production of virgin PE. If part of the emissions from production of virgin PE is allocated to the recycled PE, the difference between the recycled and conventional PE bags will be smaller. The ranking order between them is not likely to be affected. However, the ranking order between recycled PE, paper and cotton could potentially be shifted.

Cotton and paper bags can score well if waste incineration is the dominating waste-management option. Since they are produced from renewable raw materials, their incineration does not contribute to climate change. In contrast, the raw material is 100% fossil for the PE bags and to a high degree fossil also for the biodegradable bag. Producing and incinerating these bags increases the CO_2 concentration in the atmosphere.

The reason why a cotton bag can score well in this study might be that it is assumed to replace 100 single-use bags. Kimmel (2014) observes that a durable PP bag in the US is used on average 14.6 times (see Section 3.3). If the cotton bag replaces just 14.6 single-use bags, the environmental impacts per functional unit is almost seven times higher than what is reported by Mattila et al. (2011).

The reason why a paper bag can score well in the study might be that the data on paper production is from a Finnish mill. As stated by Mattila et al. (2011), Scandinavian paper industry is dominated by integrated pulp and paper mills driven, to a large extent, by the energy in the pulpwood. In contrast, for example, Muthu et al. (2011) state that paper production requires a “tremendous amount” of fossil fuel. This can explain part of the difference in the results between the studies. It also emphasises that the energy source in the paper production is important for the climate comparison of paper and plastic bags.

The relative competitiveness of cotton and paper bags is improved in this study because the plastic bags are heavier than in other studies.

The biodegradable bag can score very well when waste-management is dominated by incineration without energy recovery, or with recovered energy that replaces carbon-neutral energy sources. This is because the biodegradable bag is partly produced from renewable raw material. After use it might substitute a waste-bin liner that include more fossil carbon than the shopping bag. This means the emissions of fossil CO_2 at the waste incinerator is reduced.

Mattila et al. (2011) present a small share of the input data and no calculations. This makes it difficult to assess the validity of the study. However:

- A possible inconsistency is in the data on paper recycling: Table 1 in the paper states that 78-90% of the paper bags are recycled in the Finnish system. The description of alternative waste scenarios states that 65% of the paper is recycled in the scenario with efficient sorting of waste.
- Another inconsistency is in the assumptions that a cotton bag replaces 50-150 single-use bags and that 100 single-use bags correspond to 0.5-1.5 cotton bags. If a cotton bag replaces 50-150 single-use bags, it means that 100 single-use bags correspond to 0.67-2.0 cotton bags

Otherwise, no inconsistencies or strikingly strange data were found in the paper. The results and conclusions of the study are also not odd except, as Mattila et al. (2011) also indicate, that the paper bag scores better compared to many other studies. This might be explained by the heavier SUPBs and by the energy-efficient, largely renewable paper production.

Recycled plastic bags are likely to be good for the climate in countries where most waste is deposited at landfills. In countries where the waste management is dominated by incineration – with or without energy recovery – cotton, paper, and starch-based plastics can be better options for the climate. However, the latter depends on the weight of the bags, the number of times a durable bag is actually used, and the production process for the paper.

Table 8. Summary table for Mattila et al. (2011)

		Bags considered in study				
		Biodegradable bag	**Cotton bag**	**Paper bag**	**LDPE bag**	**RPE (60% recycled PE)**
Study Scope	Geographic region	Finland				
	Life cycle stages	Production, use stage, and end of life				
	End of life assumptions - base scenario	General Finish waste scenario in 2007 i.e. 50% of waste goes to landfill, small fraction to incineration, rest to recycling				
	Functional unit	"carrying devices for the transportation of goods from grocery stores for 1 year in Finland"				
	Material	thermoplastic starch with additives	cotton	bleached paper	LDPE	PE with 60% recycled PE
	Capacity (litres)	30-40	30-40	30-40	30-40	30-40
	Number of uses	N/A	N/A	N/A	N/A	N/A
	Weight per functional unit (g)	N/A	22 -187	N/A	N/A	N/A
	Weight per bag (g)	20	44-125	54	20	20
Indicators (results for base scenario)	Climate change	■	▒	▒	▒	□
Other comments		• The way how landfilling conditions (methane recovery or not) are assessed influences the preferability of the bags. • Paper bags and biodegradable bags need methane recovery under landfilling, otherwise they have a high impact. • Waste incineration is a better option for paper and cotton (carbon neutral). • High replacement rates lower the environmental impact (assumption cotton bags replace 100 single use plastic bags). • The energy used during paper production can have a significant effect on the paper bag impact (low emission energy lowers the impact).				

Performance Key	
□	Best
▒	Better
■	Worse

3.7 Khoo (Singapore)

3.7.1 Description

Khoo et al. (Khoo & Tan, 2010; Khoo, Tan, & Chng, 2010) are researchers in Singapore with some previous LCA experience. Observing that standard plastic bags are produced from fossil resources that are not available in Singapore, they published two scientific papers with a comparative LCA on the standard polypropylene (PP or possibly PE) bag and a bio-based bag produced from polyhydroxyalkanoates (PHA) with corn as the raw material.

The functional unit of the LCA is the carrying capacity of the standard bag: 20 kg. The conventional bag is very light, compared to other LCAs in this review. The bio-based bag is somewhat heavier and has less carrying capacity. For this reason, the quantity of material per functional unit is almost double for the bio-based bag (see Table 9). Khoo et al. did not include the use phase of the bags, nor any possible reuse.

The bio-based bag is assumed to be produced in the US and shipped to Singapore, while the standard bag is produced in Singapore based on natural gas from Indonesia and oil from the Middle East. The production of both bags involves processes that produce several different products: the refinery of oil and the wet-milling of corn (Khoo et al. 2010). The emissions of these processes are partitioned between the products used in bag production in proportion to their weight (so called mass allocation).

The electricity production, and possibly all energy supply, is in most cases modelled as the national average for the country where the electricity/energy is used. However, as a sensitivity analysis the impacts of the production of the bio-based bag is calculated with three other energy sources: coal-fired power, combined cycle technology with natural gas, and geothermal electricity.

After use, the bags are assumed to be incinerated with energy recovery or deposited at landfill (Khoo & Tan 2010). The bio-based bag can also be composted, replacing a small amount of peat. It is unclear if the calculations account for the environmental benefits of energy recovery at incineration. It includes at least the reduction of CO_2 emissions from peat production resulting from peat being replaced by composting residues.

Khoo et al. calculate the global warming potential (GWP), acidification, photochemical ozone formation, and the land use associated with waste management. They normalize the environmental impacts by dividing them by the impacts of an average person in Singapore. They find that the normalized net total impacts of waste management are small compared to the impacts of the cradle-to-gate production of the bags (Khoo & Tan 2010, Figure 8), where the latter includes raw material extraction, transports, etc. The results of Khoo et al. (2010, Figure 6) indicate that compared to the standard bag the production of the bio-based bag has, in the base case, almost three times the climate impact, and many times larger impact on the acidification.

The large bio-based bag's impacts on climate and acidification are dominated by emissions associated with the fermentation of glucose to produce PHA (Khoo et al. 2010, Figures 3-5). Emissions from, for example, the shipping bags from the US to Singapore is very small in comparison. However, the comparison is very sensitive to the supply of energy to agriculture, milling and fermentation: if the bio-based bags were produced with geothermal electricity they would score much better than the standard bag from Singapore on all environmental impacts included in the study (Khoo et al. 2010, Figure 6).

3.7.2 Meta-analysis

The study of Khoo et al. includes elements of both attributional and consequential LCA (cf. Section 2.2). The use of average data and partitioning of wet-milling and refinery emissions are consistent with ALCA. Accounting for the peat production avoided through composting is instead typical for CLCA. However, the latter has little impact on the total results, which means the study can be regarded as essentially an ALCA, estimating what part of the global emissions that belong to each bag.

The poor environmental scores for the bio-based bag in the base case partly depend on the functional unit in the study. This functional unit reflects the assumption that the number of bags used depends on how much weight they can carry. In reality, consumers often carry much less than 15 kg in a bag, because they did not buy lots of products, because the products are bulky rather than heavy, or because 15 kg is too much to carry in one hand. In all these cases a single bio-based bag might well be an adequate substitute for a standard bag. If the functional unit of the study were changed to 1 bag, the results for the standard bag would be unaffected but the results for the bio-based bag would be 25% lower. This choice of functional unit is optimistic for the bio-based bag, because the lower strength of the bio-based bag will in some cases lead to the use of an extra bag. Based on these considerations, realistic results for the bio-based bag would be lower than the results in the study but not as much as 25% lower.

The relatively poor ranking of the bio-based bag is also affected by the fact that reuse for purposes other than shopping is not accounted for. Shopping bags can be reused as liners for waste bins, reducing the need for conventional waste liner. To the extent that more than 1 bio-based bag is needed to replace 1 standard bag, the use of bio-based bags will facilitate lining of more waste bins and, hence, replace more waste liner. This effect is not included in the study. If it was included, the results would be better for both bags, but the bio-based bag would come out slightly better in the comparison. The impact on the comparison would probably be rather small, however, if a realistic assumption was made regarding how many biobags are needed, in average, to replace a standard bag. This is because a single bio-based bag is often an adequate substitute for a standard bag. In addition, the main purpose of a shopping bag is to carry products from the shop, which indicates that only a small part of the environmental burdens should be allocated to the function of lining the waste bin in an ALCA. If the study were a CLCA, the comparison would still not be affected much, because the environmental benefits of replacing a conventional, light-weight waste liner is significantly smaller than the environmental impacts of producing a shopping bag.

The sensitivity analysis of Khoo et al. (2010, Figure 6) indicates that the LCA results for the bio-based bag are completely dominated by emissions from the energy supply: when the bio-based bag is produced using geothermal energy the total emissions are nearly zero. This indicates that, for example, the shipping of bags from the US to Singapore contributes little to the total LCA results. This finding is consistent with the interpretation of Edwards and Fry (2011; see Section 3.4): intercontinental shipping appears not to be important for the overall environmental performance of bags.

If the input data and calculations of Khoo et al. were correct, a corn-based bio-based bag accounts for a much larger share of the global climate change and acidification, compared to a standard bag. However, the LCA results for the bio-based bag are completely dominated by emissions from the energy supply: when the bio-based bag is produced using geothermal energy the total emissions from the production are nearly zero (Khoo et al. 2010, Figure 6). With a future, more sustainable energy system, the bio-based bag might be better than the standard bag in all three environmental impacts.

It should be noted that several of the input data reported by Khoo et al. are, in fact, wrong or strange. For example, the incineration of 1 kg PP is reported to cause emissions of 2.34 kg of CH_4 (Khoo & Tan 2010). This figure is not only unrealistic but chemically impossible. The incineration of 1 kg PHA is reported to cause 0.537 kg of CH_4. According to Khoo et al. (2010), crude oil extraction requires 24 MJ per kg oil, which is half the energy content of the oil itself. All these numbers are strangely large.

There are also large internal inconsistencies in the papers:

- The results of Khoo & Tan (2010, Figure 4) state that the total GWP of incineration of the 4.9 g standard bag is no more than 13 g CO_2 equivalents, which indicates that the figure 2.34 kg of CH_4 per kg incinerated PE might be a simple misprint.
- Khoo et al. (2010) state that the energy efficiency for production of natural gas is 21% - an extremely low efficiency - but misinterprets this to mean that 21% of the energy in the natural gas is needed for the production of the gas.
- In Figure 6, Khoo et al. (2010) indicate that the two bags in the base case have similar impacts on photochemical ozone formation. However, Figure 5 in the same paper clearly shows that the bio-based bag has a much greater impact due to the production of PHA from glucose.
- In Figure 6, Khoo et al. (2010) also indicates that they have calculated the terrestrial eutrophication rather than acidification. This is probably a misprint, because everywhere else in the paper they write acidification. The list of emission parameters also includes SO_2, which contributes to acidification but not eutrophication.
- The abstract of Khoo et al. (2010) and the key words of Khoo & Tan (2010) state that the standard bag is produced from polyethylene. However, the main text in both papers states that it is produced from polypropylene.

Table 9. Summary table for Khoo et al. (2010) and Khoo & Tan (2010)

		Bags considered in study	
		Fossil based bag	**PHA bag**
Study Scope	Geographic region	Singapore	
	Life cycle stages	Production, end-of-life	
	End of life assumptions	landfill, incineration	landfill, incineration, composting
	Functional unit	carrying capacity of the standard bag: 20 kg	
	Material	Fossil PP (or PE)	Corn-based PHA
	Capacity (litres)	N/A	N/A
	Number of uses	1	1
	Weight per functional unit (g)	4.9	9
	Weight per bag (g)	4.9	6.8
Indicators	Climate change	□	■
	Acidification	□	■
	Ozone impacts	□	■
Other comments		• The bio-based bag is modelled with a lower carrying capacity than the fossil alternative - more material is needed per bag. • The impact of the bio-based bag is completely dominated by the energy supply during production (energy supply with high emissions).	

Performance Key	
□	Best
░	Better
■	Worse

4. Impacts of littering and degradability – two issues to be considered in future studies

4.1 Impacts of littering

Marine plastic litter and microplastics issues are a serious challenge to the environment around the world. Research suggests that microplastics can be found even in the most remote areas of the world (Allen et al., 2019). There are estimates that about 5-10 million tonnes of plastic are littered to land and oceans every year (COWI A/S and Utrecht University, 2018). Plastic bags are among the top ten items recorded by the 2013 International Coastal Cleanup (COWI A/S and Utrecht University, 2018; Werner et al., 2016). Consequently, many regulations have been put into force to reduce the consumption of SUPBs and promote the use of alternative solutions *“As of July 2018, about 66% of the countries in the world have adopted some form of legislation to regulate plastic bags. The regulations vary considerably in their comprehensiveness, but the most common form is the restriction on free retail distribution”* (UN Environment, 2018).

Accumulation of plastic litter in the maritime environment has been identified as one of the major global issues by the United Nations Environment Assembly and in the G7 Leaders declaration 2015 (Werner et al., 2016). Apart from accumulation of plastic litter in maritime and freshwater environments, there is evidence that also soil accumulates plastics (Napper & Thompson, 2019). Thus, the presence of plastic litter in the environment is a complex problem, since it can be connected to social, (e.g. aesthetic value), economic (e.g. cost to tourism, fishing), and ecological problems (e.g. mortality or sublethal effects on plants and animals) (Werner et al., 2016).

Even though the problem associated to impacts of littering is a highly relevant aspect, it has been poorly addressed in most of the LCA studies. The main reason is that there is no standard impact category developed for modelling and assessing the impacts of litter in LCA (COWI A/S and Utrecht University, 2018). Several studies attempted to address the impacts of littering in a quantitative way or semiquantitative way (Civancik-Uslu et al., 2019; Chris Edwards & Fry, 2011; Environment Australia, 2002) or in a qualitative way (COWI A/S and Utrecht University, 2018; Lewis et al., 2010). Moreover, there are several ongoing projects that are developing the methodology to include environmental impacts of littering in LCA. For instance, the project MariLCA was launched in May 2019 to integrate potential environmental impacts of marine litter, especially plastic, in LCA results (MariLCA, 2019). Another example is the Plastic Leak Project

(PLP) that aims to develop smart metrics to enable industries and governments to forecast and map leakages along their life cycle (Quantis, 2019).

Other studies state that the problem associated to impacts of littering is not so relevant specifically for LCAs of plastic bags. For instance, the study from Ireland estimated that plastic bags represent a minor fraction of the litter (<1% wt) (EuroCommerce, 2004). A study that analysed the problem of littering in Israel estimated that less than 6% of the plastic bags become litter (EuroCommerce, 2004; Lewis et al., 2010). They suggest that plastic litter is a problem of perception rather than a real issue, as it has not been possible to quantify the environmental nuisance due to litter from plastic bags. Those studies claim that injury and death to marine species have been linked to plastic litter in general, rather than plastic bags alone (Lewis et al., 2010).

It has also been discussed that it is not certain that all plastics referred as “bio-based[1]”, “biodegradable” (or similar) are more advantageous in terms of reducing marine litter than fossil-based plastics (COWI A/S and Utrecht University, 2018; Instituto Nacional de Ecologia, 2009; Napper & Thompson, 2019). On the other hand, there are also studies investigating the biodegradation rate of different polymers and suggest examples of polymers that can undergo rapid biodegradation (Chinaglia et al., 2018).

4.2 Degradable Plastics

Degradable plastics can be grouped into two major classes (UNEP, 2015) - oxo-degradable plastics and biodegradable plastics. There have been developments specifically aiming at degradability under marine conditions (Tavares Kennedy, 2018), and Kjeldsen et al. (2019) provide an overview of related testing standards.

Oxo-degradable plastics

Oxo-degradable plastics[2] are conventional plastics which include a metal compound increasing the initial rate of fragmentation and oxidation of the plastic. The degradation process of oxo-degradable bags can be summarised into two steps: (1) fragmentation, during this step the plastic is broken down into smaller fragments via chemical oxidation reactions (Roy et al., 2011) and (2) bio- assimilation, meaning the plastic fragments are consumed by microorganisms resulting in the release of CO_2 and water to the atmosphere (Roy et al., 2011; Thomas et al., 2012). The speed and extent of both steps depend heavily on the degradation environment; in certain surroundings (e.g., in sea water, under soil) particularly bio-assimilation can take unreasonably long.

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[1] The working group on environmental aspects of plastic develops standards in the areas of bio-based plastics, biodegradable plastics, carbon dioxide imprint and other environmental impacts, characterization of plastic leaks (including microplastics), plastic recycling and resource efficiency (incl. Circular economy).(https://www.sis.se/standardutveckling/tksidor/tk100199/sistk156/)

[2] It should be noted that oxo-degradable plastics were recently banned in the context of the EU directive on single-use plastic products.(https://www.european-bioplastics.org/the-debate-biodegradable-and-compostable-plastic-bags/)

This was confirmed by a report from the EU Commission (European Commission, 2018b) as well as other studies. For example, Roy et al. (2011) found that oxo-degradable PE (polyethylene) only fragmented when tested under open air conditions. Similar results were also stated by Napper et al. (2019), who found that after 9 months in open air oxo-degradable plastic bags had only fragmented. In addition to open air conditions, Napper et al. (2019) also tested the effect of submerging the bags under sea water and of burying the bags under ground. In both cases the bags did not degrade and were still functional after 3 years. This confirmed earlier findings by Adamcova et al. (2017) who had tested degradation after 48 months in a landfill. These findings are not surprising as oxo-degradable plastics were set up to degrade in the open air and to the exposure of UV radiation (European Commission, 2016; Scott, 2009). Both conditions can be hard to meet in landfills and in the sea (Napper & Thompson, 2019).

Biodegradable plastics

Biodegradable plastics are designed to break down easily via hydrolysis (i.e., the breaking down of chemical bonds due to the reaction with water). Compostable plastics are a subcategory of biodegradable plastics designed to degrade under managed terrestrial conditions including forced aeration and elevated temperatures (European Commission, 2018b; UNEP, 2016) - see also ISO 17088:2012 (ISO, 2012) and CEN EN 13432:2000 (CEN EN, 2000).

The chain of degradation processes for biodegradable plastics is similar to the chain for oxo-degradable plastics. First the plastic fragments due to the exposure to e.g. sunlight or water (Bátori et al., 2018). Then the fragments are assimilated by microorganisms, which use various extra- and intracellular enzymes in the process (Bátori et al., 2018; Zeng et al., 2016). Depending on whether the assimilation occurs under aerobic or anaerobic conditions, CO_2 (aerobic conditions) or a mix of CO_2 and methane (anaerobic conditions) is released as part of the process (COWI A/S and Utrecht University, 2018). The speed of degradation depends on various factors such as the availability of other, more preferable nutrients and the dominance of the microorganisms degrading the plastic (Haider et al., 2019). Temperature, pH and humidity are also of importance. For example, Emadian et al. (2017) found in their review study, that the degradation of PHA (Polyhydroxyalkanoate) in sea water changes with water temperature. Haider et al. (2019) state in their review on biodegradable plastics that PLA (polylactic acid) degrades faster under industrial composting conditions than under household composting, due to higher temperatures and higher humidity in industrial sites.

Further factors influencing the speed of degradation are the availability of oxygen and UV light. UNEP (2016) pointed out that biodegradable plastics degrade very slowly in sea water, as oxygen concentration and the exposure to UV light is lower compared to open air conditions. Similar findings were also reported by Karamanlioglu et al. (2017) in their review on PLA biodegradability. In addition, they also state that PLA, when buried in soil, showed no changes in physical properties after one year and only some degradation after two years. Again, this is due to low oxygen and UV exposure. Oxygen exposure seems to be particularly important as biodegradable plastics were designed to specifically degrade in aerobic conditions (COWI A/S and Utrecht University, 2018).

To summarise, degradable plastics do not degrade with the same rate and to the same extent in all environments. Plastics classified as oxo-degradable seem to only fragment i.e. they do not fully degrade; leaving visible and invisible residues behind. For biodegradable plastics, the availability of oxygen and the exposure to UV light are two key factors to their complete degradation. Other factors are surrounding temperature and humidity, which were found to be favorable in industrial composting sites. These sites are fully managed, and plastics labelled as compostable are intended to be treated there and not to be left in the environment. LCAs assessing biodegradable plastic products should ideally take all these considerations into account and not assume full degradation with zero impacts at the end of life.

5. Discussion and conclusions

5.1 Environmental impacts of bags

This study is not the first meta-LCA comparing bags made of different materials. Previous meta-analyses (EuroCommerce, 2004; Greene, 2011; Lewis et al., 2010) reviewed LCAs published between 1990 and 2011 from a range of countries: Australia, Canada, France, Ireland, Israel, Scotland, Switzerland, and USA. These LCAs varied in terms of functional units and geographical and technological system boundaries. However, some common conclusions can be drawn from the previous meta-analyses:

- Reusable PE bags have lower environmental impacts than single-use bags, but the results are sensitive to usage rates. The usage rates that make the reusable plastic bag a better option from an environmental point of view vary from 4 times (EuroCommerce, 2004) to 20 times for reusable bags made of virgin material and 8 times for reusable bags made of recycled PE (Greene, 2011).
- SUPBs rank better than single-use paper bags and single-use biodegradable bags in almost all environmental categories, except impacts of littering.
- Data on biodegradable bags are uncertain but it can be concluded that they have lower contribution to impacts from marine littering than PE bags and lower contribution to GHG emissions than paper bags (EuroCommerce, 2004).

The more recent LCAs included in this report confirm most of these conclusions, with some additions and modifications. In summary, they indicate that:

- Single-use LDPE or HDPE bags rank worse than other bags in terms of littering potential. However, the ranking order of bags in terms of littering potential is more or less opposite to the ranking in terms of other environmental indicators (Civancik-Uslu et al. 2019). The weight of the bags contributes to this difference: making a bag heavier will make it more difficult for the wind to catch, hence reducing probability to become litter, but it will increase all other environmental impacts of the bag.
- LDPE produced from recycled plastics or renewable resources has much less climate impact than fossil-based LDPE, but does not solve the problem associated to impacts of littering. Bio-based LDPE is also worse than conventional LDPE in other environmental aspects (COWI A/S and Utrecht University 2018).
- A reusable LDPE bag has lower climate impacts than conventional single-use plastic bags, if they are used 5-10 times more than the single-use bag (Edwards et al. 2011; Kimmel 2014; Civancuk-Uslu et al. 2019). However, Kimmel (2014) finds that the average reuse rate in the US is just 3.1 times.
- Durable PP bags are heavier than reusable LDPE bags, but they are also more durable. In order for PP bags to be environmentally competitive with LDPE bags, they need to be used more times.

The data already suggest that they are used on average 14.6 times in the US (Kimmel 2014) which is approximately what is needed for PP bags to be competitive with conventional, single-use plastic bags (Edwards and Fry 2011; Kimmel 2014).

- A cotton bag must be used even more times to be environmentally competitive. Mattila et al. (2011) state that a cotton bag reused 50-150 times is likely to be better for the climate if the waste-management system is dominated by incineration or efficient sorting and recovery of the waste. However, Edwards and Fry (2011) find that the cotton bag must be reused hundreds of times to be environmentally competitive to SUPBs.
- Paper bags score worse than fossil-based single-use bags in terms of eutrophication, and often also on climate and other environmental aspects. Kimmel (2014) finds that the paper bag with 100% recycled fibres scores better than the kraft-paper bag in all environmental aspects, but still worse than the SUPBs in all impacts except acidification, and freshwater and marine toxicity. In contrast, Mattila et al. (2011) and Dahlgren & Stripple (2016) find that kraft-paper bags score relatively well in climate. Together the studies imply that a paper bag can be better for the climate than SUPBs, if the latter is heavy, if the paper is produced in efficient integrated mills driven by renewable energy, and if the waste-management system is dominated by recycling and incineration. They can also be environmentally competitive if they are reused several times (Edwards and Fry 2011).
- A starch-based (biodegradable) bag has no significant environmental benefits compared to conventional SUPBs in the reviewed studies, besides reduced impacts of littering. It has a large impact on the climate because the production of fossil-based co-polyesters (COWI A/S and Utrecht University 2018) and because it is assumed to degrade in landfills, forming methane (cf. Mattila et al. 2011).
- Adding a prodegradant to conventional HDPE (oxo-biodegradation) to reduce the visual impacts of littering might increase other environmental impacts, but only slightly since the degradable plastic bag is assumed not to degrade in landfills (Edwards and Fry 2011; Edwards and Parker 2012).

Apart from the general observations, the following factors also influence the impacts of different bags, and strategies need to be tailored for these settings.

Weight of the bag

The environmental impacts of a bag are proportional to the quantity of material used to make the bag. The weight of the paper bag is almost the same in all studies: approximately 55 g. However, the weight of other bags varies between studies, at least in part because the dominating design of bags in each country. According to the studies in this review, the conventional SUPB weighs less than 5 g in Singapore, about 6 g in China, India and the US, and almost 18 g in Spain and the UK, and 20 g in Finland. These numbers suggest there is a correlation between light weight of the common plastic bag and a large number of bags per household in the country. This might be because the heavier bags are typically both bigger and sturdier.

Number of uses

One important factor to consider when making choices between bags is the number of bags used. The average number of bags used by consumers per year seems to vary significantly between countries. For example, according to studies in this review, an average Chinese consumer uses more than 1000 bags per year, which is similar to an average supermarket shopper in the UK. However, an average Spanish household uses 400 bags per year, and an average Finnish household just 100 bags per year. The difference might be due to the types of bags that are made available in shops and the consumer behaviour in specific countries and regions. This indicates that the choice of bags each consumer makes is more important in China and the UK, compared to Finland.

In general, the environmental impacts per person or household is inversely proportional to the number of times each bag is used. This will vary depending on the design of the bag. A paper bag, for example, is more likely to be reused if it has durable handles and can be neatly folded for storage. The actual reuse rate in the end depends on consumer behaviour which also varies between countries. Unfortunately, there is a lack of data on the actual reuse rate of bags.

Indirect/unforeseen/complex impacts [land-use change]

The climate impacts of paper, starch and bio-based LDPE depends on how the production and extraction of the biomass affects the land use and its carbon flows. The impact can be positive or negative depending on, for example, the forest management. A change in the land-use at one site can also have indirect impacts on the land-use elsewhere. This is discussed in the BIOSPRI study (COWI A/S and Utrecht University 2018) but not accounted for in other studies. The direct and indirect impacts on land use are not accounted for in this meta-analysis, because of the complexity of this issue. It is one example of how the choice between bags can have impacts beyond the scope of the study. Other indirect, complex and partly unforeseen impacts can occur in the waste-management system, the raw material markets, etc.

Waste Management system not well organised

The impacts of the bags also depend heavily on the waste-management system where the bags are disposed of and processed. This means that the same bags perform differently in their end-of-life in different countries, regions and contexts, depending on the local waste-management system. If the waste management system is not well organised, the risk of marine and terrestrial littering and the problem of microplastics are greater. Banning or incentivising significant reduction (e.g., through pricing or taxation) of conventional single-use plastic bags makes the most sense here. As clear from above, these bags have the highest probability of becoming litter. Replacing them by cotton bags might be the most effective way to reduce the impacts of littering, because they are durable, degradable and can be informally recycled as rags. Degradable bags of paper or starch-based plastics and durable plastic bags might also be good options.

Effective waste collection and sanitary landfills

If the waste collection is effective and waste-management is dominated by sanitary landfills, the carbon in conventional waste plastics (e.g., LDPE, HDPE and PP) is stored there for a very long time. This holds even if the plastics are produced from renewable raw materials and also seems to be true for oxo-degradable plastics. This reduces the climate impact of the bags. Paper and starch-based bags, on the other hand, contribute to global warming by degrading to form methane. The banning of conventional plastic bags makes perhaps the least sense here, although the total climate impacts of plastic bags will probably be lower if they are produced from renewable or recycled raw materials.

Ineffective waste collection and sanitary landfills

If the waste collection is not really effective and the risk of littering is significant, a shift to starch-based (biodegradable), paper and/or cotton bags would help reduce both visual impacts of littering and microplastics. However, in countries where the waste management system is dominated by landfills, these bags are likely to increase the impacts on climate and other environmental burdens compared to conventional plastic bags. A system of durable bags combined with actions to increase the reuse rate of these bags might be the best way forward in countries with sanitary landfills and significant rates of littering.

Incineration with low rates of littering

When the waste management system is dominated by incineration, with or without energy recovery, the carbon in the fossil or bio-based waste is released as CO_2. The incineration of bags produced from fossil resources will affect the climate. If the bags are produced from paper, cotton or purely bio-based plastics, incineration can be considered climate neutral. Note that although starch is bio-based, starch-based bags include a significant share of co-polyesters produced from fossil resources. In countries with incineration and low rates of littering, a shift to purely bio-based plastics will probably reduce the climate impacts of bags. A shift to paper and cotton might also have climate benefits, depending on how the materials are produced and how many times the bags are used.

Incineration with significant rates of littering

In countries with waste incineration and significant rates of littering, paper and/or cotton might be the best options to reduce the impact of littering. They do not create microplastics and are climate neutral when incinerated. Again, however, the environmental performance of the paper and cotton bags depends on how they are produced and how many times they are used.

Recycling and biological treatment

In countries with a high degree of recycling, the environmental performance of bags depends on what is displaced by the recycled material. This also varies between bags. The recycling of LDPE bags gives a much greater climate benefit than the composting of starch-based bags, if the recycled LDPE replaces virgin, fossil-based LDPE (COWI A/S and Utrecht University 2018). This is because compost residues replace little more than fertilizers. The recycling of paper bags can also give environmental benefits, but the climate benefits are highly dependent on the fuel used in the virgin production and recycling processes.

Degradable plastic bags do not fit well in countries with a system for recycling of plastic bags. The study by Environment Australia (2002) highlighted that biodegradable plastic bags might create a problem in the current plastic film recycling industry mainly due to the risk of their presence in the products made of recycled material. Also, if biodegradable material gets into the stream for production of irrigation piping (that contains over 90% recycled content), it can cause them to degrade and fail their application during use phase (Environment Australia, 2002). The LCAs reviewed do not account for such impacts. If degradable plastic bags are still used in a country with recycling of plastic bags, they should be designed to make it easy to see that they are non-recyclable.

On the other hand, the plastics LDPE, HDPE and PP, whether produced from fossil or renewable resources, do not degrade in biological waste processes. These plastics might clog the processes and will also remain in the residues from these processes. This might restrict the applicability of the composting and digestion residues and, hence, reduce their potential environmental benefits. The LCAs reviewed do not address these issues. Bags for collecting biological waste need to be produced from degradable materials. They should look distinctively different from conventional plastic bags to reduce the risk of consumers using the conventional plastic bags for this purpose.

Transport

The transport of bags affects the environment less than the production of the material and the waste management. Long-distance shipment of bags between continents has less impacts than long-distance road transports within continents (see, e.g., Edwards and Fry, 2011)

Reducing impacts of litter

From this discussion we conclude that the problems of terrestrial and marine litter and microplastics can be reduced by shifting away from the use of single-use HDPE, LDPE and PP bags; however:

- A shift to bio-based LDPE will not help in this respect.
- A shift to reusable LDPE bags or durable PP bags might help if the consumer uses these bags many times, and they are properly managed (e.g., collected and recycled) at the end of their life; otherwise such a shift will only mean that the litter and microplastic originate from heavier bags.
- A shift from conventional HDPE and LDPE bags to degradable bags will help reducing the visual and physical impacts of littering (although oxo-degradable bags do not solve the problem of microplastics). The main drawback is that they do not fit well in a context where plastic bags are mechanically recycled, unless the technology ensures that degradable bags can be separated from other bags.
- A shift to paper or cotton bags will help reducing impacts from both littering and microplastics. However, paper and cotton bags are likely to have more impacts on the climate, eutrophication and

acidification, compared to the conventional plastic bags, at least in parts of the world where the waste management system is dominated by landfilling. In countries with waste incineration, they can be competitive from a climate perspective and also from other environmental aspects if they are efficiently produced and have a good rate of reuse.

It can be concluded that reducing environmental impacts of bags is not just about choosing, banning, recommending or prescribing specific materials, but also about changing the design and use model of the bags (from single-use to reusable) as well as consumer behaviour.

Input data

The results of an LCA depend on the choice of input data. The LCAs reviewed here follow common practice in that they are based on data reflecting the environmental performance in previous years. However, in some cases the data are rather old. This is likely to affect the results more for bags produced from innovative materials than for the conventional materials. Conventional plastics, paper and cotton have a long history of large-scale production. This indicates that the production technology is mature and that further improvements in the efficiency of these processes is gradual and slow. For innovative materials like bio-based plastics and biodegradable plastics, the production processes are likely to change quickly. This makes the use of recent data important for a fair comparison of the bags. Furthermore, continued developments of the production processes are likely to make the innovative materials more environmentally competitive in the future than they are today.

5.2 Making use of life cycle assessment

Many LCAs have been carried out to compare shopping bags. A large share of these seems to be produced by inexperienced LCA practitioners. There are several reasons why a comparison of bags might often be the first LCA a student or researcher conducts. Bags are simple products, which makes the LCA more manageable for the inexperienced practitioner. The choice between carrier bags is a decision we all face frequently, and there is a genuine uncertainty regarding which choice is the best for the environment.

An LCA is a complex study, even when the product is simple. There is a significant risk that it contains important errors. A peer review contributes to eliminating such errors. However, a peer review is not in itself a guarantee that the study does not include important errors. This is illustrated by the multiple errors in the scientifically reviewed and published papers by Khoo et al. (2010) and Khoo & Tan (2010). The double-counting of environmental benefits of recycling in the report by Kimmel (2014) demonstrates that a combination of ISO compliance and a peer review is also not always enough. Experience is important to make the LCA as reliable as possible. It should ideally be conducted by an experienced LCA practitioner and/or with close supervision from an experienced LCA expert. They should have enough resources to do a thorough study, and the study should go through a peer review.

Results from reliable LCAs can still contradict each other. This is because LCA is a family of methods. The results depend on the specific choices made in that study regarding, for example, system boundaries and input data. A transparent LCA report includes information on the important methodological choices. However, it can be difficult for a non-LCA expert to understand the reasons for making these choices and to assess the relevance of the system boundaries etc. Policy makers and other decision-makers might need help from LCA experts to interpret the LCA and its results.

Rather than arguing for or against the methodological choices in a study, the LCA expert that interprets a reliable LCA should aim to clarify what kind of knowledge is gained from the LCA results. An LCA can be designed to estimate how our environmental impacts are affected by the production and use of a bag. It can also be designed to estimate what share of our environmental impacts belong to the bag. These are two different things. Clarifying what kind of knowledge is gained from the results of the reviewed studies is precisely the aim of this report.

There is much to learn from an LCA, other than from the final results (Figure 1). An LCA is a learning process, and the LCA practitioner gains much knowledge from the study. This knowledge includes, insights regarding what is important in the life cycle and what is certain regarding its environmental impacts. Such insights can be a valuable or even crucial input to decision-making processes. This means decision-makers benefit from deeper understanding of the LCA. When possible, they should get involved in the LCA to gain as much of the insights as possible directly from the study and the LCA practitioner. When faced with a completed LCA, other experienced LCA experts can help interpreting the study to gain as much knowledge from it as possible.

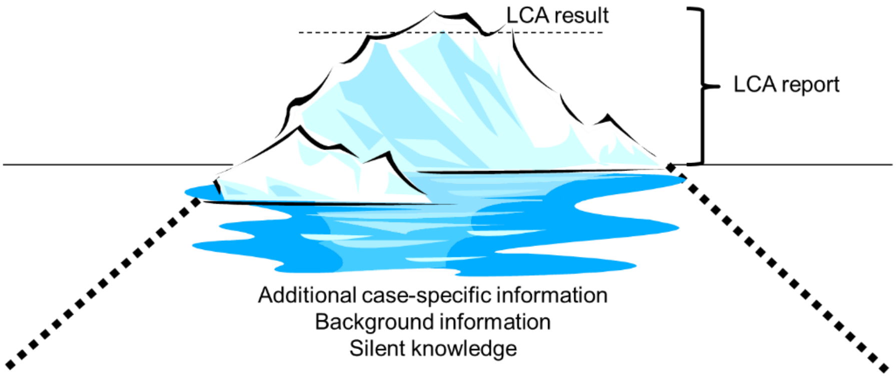

Figure 1. The knowledge gained from an LCA illustrated by an iceberg. It is much more than the final results. Potentially important knowledge is not even in the LCA report but only in the head of the LCA practitioner (Ekvall 2012).

Much of the above holds not only for LCAs on bags, but for LCA in general. However, there are a few specific points to have in mind when conducting or interpreting an LCA of bags:

- A one-on-one comparison of bags with different sizes is not accurate, because consumers might need a larger number of bags if they are smaller. On the other hand, the functionality of the bags is also not accurately reflected by their capacity, because a small bag is often a sufficient substitute for a larger bag. The most accurate comparison is somewhere between the two extremes: assuming the functionality of the bag is independent of its size, and assuming the functionality is proportional to its size.
- A waste-management system dominated by controlled landfills will have lower impacts for plastic bags in the LCA, while a waste-management system dominated by waste incineration will have lower impacts for paper bags, based on the performance of materials in different recycling systems
- The LCA should include country-specific data, particularly on the waste-management system, the weight of the bags and the number of times each bag is used, because these factors vary between countries and have an important impact on the LCA results.
- The input data should be as recent as possible. This is particularly important for modelling the production of innovative materials, because of the rapid changes that can occur in new technological processes.

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