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Life Cycle Initiative

# Single-use plastic bottles and their alternatives –

## Recommendations from Life Cycle Assessments

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## Recommendations from Life Cycle Assessments

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# Executive Summary

Among the most commonly used types of beverage bottles are bottles made from plastics for single use. The environmental impact of single-use plastic bottles has been widely discussed in society. For example, they are among the top plastic products found on beaches, contributing to the growing littering of marine and terrestrial ecosystems. To mitigate the environmental problems of single-use plastic bottles, there is a need to consider alternative solutions. This report summarises current knowledge about the environmental performance of single-use plastic bottles and their alternatives, and analysis how this knowledge can be used to guide policy makers and other actors.

The study considers single-use plastic bottles and alternatives that could potentially replace them from a functional and transportation point of view. The following alternatives are considered: glass bottle (single-use), aluminium can (single-use), carton laminated packaging systems (single-use), reusable steel and aluminium bottles, as well as non-container means for providing drinking water (see table below). Reusable glass bottles were considered in one study only as part of sensitivity analysis.

The report includes a meta-analysis of seven life cycle assessment (LCA) publications, see below table.

| Type of material / Publication | Plastic (single-use) | Glass (single-use) | Aluminium (single-use) | Carton laminated (single-use) | Steel, aluminium (reusable) | Non-container means | Geographic scope | Functional unit |
|---|---|---|---|---|---|---|---|---|
| **LCA studies comparing different types of single-use plastic bottles** | | | | | | | | |
| Virgin, recycled, and bio-based PET bottles (Benavides et al. 2018) | PET from fossil fuels, biomass, recycled plastic | | | | | | USA | 0.5 l PET bottle |
| Fossil and bio-based PET bottles (Chen et al. 2016) | PET from fossil fuels and biomass | | | | | | USA | 1 kg of PET bottles (equals the weight of approximately 100 bottles with 0.5 l capacity) |
| PLA and PET drinking water bottles (Papong et al. 2014) | PET, PLA | | | | | | Thailand | 1000 units of 0.25 l drinking water bottles |
| **LCA studies comparing single-use plastic bottles with beverage containers made of other materials** | | | | | | | | |
| PET, HDPE, PP, glass and carton packaging systems (Schlecht et al. 2019) | PET, HDPE | | | | | | Denmark, Finland, Norway and Sweden | 1000 l packaging volume for chilled or ambient beverage at the point of sale |
| PET, HDPE, PP, glass and carton packaging systems (Schlecht et al. 2018) | PET, HDPE, PP | | | | | | Belgium, Ireland, the Netherlands and the UK | 1000 l packaging volume for chilled or ambient beverage at the point of sale |
| Glass bottles, aluminium cans and PET bottles (Amienyo et al. 2013) | | reuse is studied in sensitivity analysis | | | | | the UK | 1 l of a carbonated drink |
| Reusable steel or aluminium bottles (non peer-reviewed) | | | | | | | N/A | NA |
| **LCA studies comparing single-use plastic bottles and non-container means for providing drinking water** | | | | | | | | |
| PET bottles and non-container means for providing drinking water (Garcia-Suarez et al, 2019) | | | | | | | India | 20.000 l of drinking water at consumer's home |

Peer-reviewed publications (included in meta-analysis) Non peer-reviewed publications (discussed but not included in meta-analysis)

The below table summarises the findings of the meta-analysis, including some of the environmental benefits and drawbacks of single-use plastic bottles compared to their alternatives. The three impact categories included in the table are just a few of the environmental impacts covered by the analysed studies, they are further discussed in our report. Also note that some important environmental issues are not covered by the studies in the meta-analysis, such as terrestrial and marine littering, or availability of agricultural land.

**Environmental impacts of the products studied: Summary Table**

| Impact indicator | Climate change | | Acidification | | Eutrophication | | Comments |
|---|---|---|---|---|---|---|---|
| **Publication** | **Best** | **Worst** | **Best** | **Worst** | **Best** | **Worst** | |
| **LCA studies comparing different types of single-use plastic bottles** | | | | | | | |
| Virgin, recycled, and bio-based PET bottles (Benavides et al. 2018) | 100% bio-based PET | 100% fossil-based PET | N/A | N/A | N/A | N/A | Considered also water consumption and fossil fuel consumption as impact indicators. |
| Fossil and bio-based PET bottles (Chen et al. 2016) | excl avoided impacts -100% fossil-based PET; incl avoided impacts- 100% bio-based PET (70% wood, 30% corn or 30% wheat straw) | incl and excl avoided impacts- 100% bio-based PET (70% corn stover, 30% switchgrass); incl avoided impacts- 70% fossil-based PET with 30% biobased- (switchgrass) PET | incl and excl avoided impacts- 100% fossil-based PET | incl and excl avoided impacts- 100% bio-based PET (70% corn stover, 30% switchgrass) | incl and excl avoided impacts- 100% fossil-based PET | incl and excl avoided impacts- 100% bio-based PET (70% corn stover, 30% switchgrass) | Showed two types of results: with avoided impacts and without. In terms of acidification, eutrophication and ozone impacts, the best and worst options are the same for both type of results (with and without avoided impacts). |
| PLA and PET drinking water bottles (Papong et al. 2014) | Fossil-based PET (recycling at end-of-life) | Bio-based PLA from Cassava (landfill without energy recovery at end-of-life) | N/A | N/A | N/A | N/A | Study shows results for system boundaries including and excluding end-of-life processes. Results here are based on the inclusion of end-of-life. Acidification, eutrophication and other impacts are covered by the results excluding end-of-life. |
| **LCA studies comparing single-use plastic bottles with beverage containers made of other materials** | | | | | | | |
| PET, HDPE, PP, glass and carton packaging systems (Schlecht et al. 2019)<br>PET, HDPE, PP, glass and carton packaging systems (Schlecht et al. 2018) | Cartons with bio-based PE cap and PET bottles- for the segment of still water | Depends on the segment | Beverage cartons with fossil-based cap (most of the segments) | Depends on the segment | Beverage cartons with fossil-based cap (most of the segments) | Depends on the segment | General observations are shown here. However different types of packaging were only compared within one type of segment (considering the type of beverage, volume and country). Each packaging system shows different environmental performance depending on the market and segment it is used for. See the original reports for more details. |
| Glass bottles, aluminium cans and PET bottles (Amienyo et al. 2013) | PET bottles (2 l) | Glass bottles (0.75 l) | PET bottles (2 l) | Glass bottles (0.75 l) | Aluminium cans (0.33 l) | PET bottles (0.5 l) | Sensitivity analysis showed that glass bottles (0.75 l) need to be reused at least three times to be environmentally equivalent to aluminium cans and PET bottles (0.5 l) . |
| Reusable steel or aluminium bottles (non-peer reviewed) | Excluded from meta-analysis. However the studies indicate potential environmental benefits of reusable steel and aluminium bottles in comparison to single-use plastic bottles, but that these depend considerably on number of uses and vary between impact categories. Further studies are needed. | | | | | | |
| **LCA studies comparing single-use plastic bottles and non-container means for providing drinking water** | | | | | | | |
| Plastic bottles and non-container means for providing drinking water (Garcia-Suarez et al. 2019) | Tap water purified with a domestic reverse-osmosis device | Water in PET bottle | Tap water purified with a domestic reverse-osmosis device | Water in PET bottle | Boiled tap water | Water in PET bottle | Water supplied by bottles is the worst option for all studied impact categories, also considering the fifteen additional impact categories shown in the appendix of the study (not shown in this report). |

# EXECUTIVE SUMMARY

## CRITICAL PARAMETERS INFLUENCING THE ENVIRONMENTAL IMPACT OF PLASTIC BOTTLES AND THEIR ALTERNATIVES:

- **Container material**. The studies show great differences between container materials. For example, single-use glass bottles were found to have a worse environmental performance than their alternatives for almost all impact categories. In the comparisons of different container materials there are, however, often trade-offs between impact categories – for example, one study shows 2 litre PET bottles to be environmentally preferable in all impact categories, except for eutrophication, ozone layer depletion and terrestrial ecotoxicity potential, where aluminium cans show better results.

- **Maturity of the technologies and production routes**. Single-use plastic bottles may be produced from fossil or bio-based resources, from virgin or recycled resources, which greatly influences their environmental impact. Whether a solution for providing beverages is a novel small-scale solution or an established large-scale solution may also considerably influence its environmental performance – but the environmental impact of the small-scale solution is more likely to decrease over time. For example, technologies for producing bio-based plastic bottles are generally more novel and small-scale than technologies for producing fossil-based plastic bottles. There are also differences within each of these categories, for example there are many possible bio-based resources causing different environmental impact, and there are several subsequent routes for producing bio-based plastics out of these resources.

- **End of life practices** significantly influence the environmental impact of beverage containers. This includes collection, recycling and reuse rates, as well as to what extent materials are eventually landfilled or incinerated with energy recovery. For example, one study found that glass bottles need to be reused at least three times to be environmentally comparable with aluminium cans and PET bottles, and that increasing recycling of PET bottles from 24% to 60% can reduce climate impact by 50%.

- **Geographical context**. The location where production, use and end-of-life take place affects technologies used, user behaviour and other parameters, influencing the environmental impact of solutions for providing beverages. Recycling rate of containers, such as PET bottles or aluminium cans, are an example of an important geographically dependent parameter.

- **Volume of the beverage container**. For example, one study shows cartons to be the best choice in all studied environmental impacts for juice packaging of small volumes, while for bigger volumes no general advantage was observed. Another example shows that, for providing a set amount of beverage, larger PET bottles are environmentally preferable to smaller ones.

## RECOMMENDATIONS FOR POLICY MAKERS:

- **Policies must consider functional differences** between solutions for providing beverages. This includes, for example, the container's capacity to deliver different beverages and volumes to different customers at different times, or their potential for reuse (formal or not). For example, a 0.5 litre plastic bottle, or another beverage container of similar size, is portable and may be reusable, whereas a larger container or boiled tap water may not provide the same accessibility.

- **Policies must consider differences in production within a material category**, as there are sometimes larger differences in the environmental impact within a single container material than between container materials due to variations in production. For example, for PET bottles, the choice between using fossil-based, recycled or bio-based resources (or different types of bio-based resources) makes a considerable difference to their environmental impact.

- **Policies must account for differences in technology maturity.** Whether a certain beverage solution is novel or established, small-or large-scale must be considered in policy making, as its current environmental performance may not be representative for its possible future environmental performance.

- **Policies must consider differences in end-of-life practices**, as there are large differences in the environmental impact of beverage containers depending on collection, recycling and reuse rates, and to what extent materials are eventually landfilled or incinerated with energy recovery. For example, policies concerning PET bottles and aluminium cans should distinguish between countries with high recycling rates due to the existence of deposit systems, and countries without deposit systems, which generally have lower recycling rates.

- **Policies must account for future changes** of production technologies, end-of-life practices and other aspects of the product system influencing its environmental impact. The environmental impact of any production technology will likely change in the future, for example as a result of changing energy systems. End-of-life practices are also expected to change, for example due to technological advancements  or other policies being implemented. Policy making must therefore rely on future scenario assessments, as a complement to studies on current (and past) product systems.

- **Policies must be geographically adapted**, as many product system parameters differ between countries and regions. Such parameters are for example: the feedstock that is likely used for bio-based plastics, whether tap water is a direct source of safe drinking water or must be boiled prior to being consumed, or to what extent landfilling, incineration or recycling can be expected to be employed at end-of-life.

- **Policies must recognise and manage trade-offs and risks of burden-shifting between environmental impacts.** Policy making must consider all potentially relevant impact categories, to avoid the risk of burden-shifting i.e.the mitigation of  one environmental issue at the expense of another. Potentially this calls for the combination of policies that jointly are capable of addressing or balancing several relevant environmental issues.

- **Policies must be based on several sources for information on environmental impact.** LCA is an excellent tool for providing scientifically based guidance related to many environmental issues, but the characterisation of some environmental impacts are better than others and some relevant impact categories may not be covered. For example, impacts from littering or toxic effects of microplastics released to the marine environment are seldom included in LCAs of plastic bottles and their alternatives. Also some resourse constraints, which are highly dependendent on the scale of production – such as availability of agricultural land – are seldom incuded in such LCAs. This may be particularly important when comparing bottles made of recycled and bio-based resources, or bottles of different bio-based content (e.g., forestry residues vs. agricultural crops). Therefore, in contexts related to plastic bottles and their alternatives, policy makers should complement the result of LCA studies with additional sources of environmental impact information.

Apart from the above bullet points, the report sheds light on the benefits and challenges of LCA as a method to assess the environmental impact of beverage containers, and provides guidance that can improve the comprehensiveness, consistency and accuracy of future LCA studies.

This meta-analysis cannot be used as the sole source for environmentally related advice on specific policy making, such as specific prohibition of specific containers, taxes and fees, or labelling. But the meta-analysis can give recommendations of aspects that policy making should consider.

# Abbreviations

| TERM | DEFINITION |
|---|---|
| EG | Ethylene glycol |
| EU | European Union |
| GWP | Global warming potential |
| HDPE | High-density polyethylene |
| ISO | International Organization for Standardization |
| LCA | Life cycle assessment |
| LDPE | Low-density polyethylene |
| PP | Polypropylene |
| PE | Polyethylene |
| PET | Polyethylene terephthalate |
| PLA | Polyactic acid |
| PS | Polystyrene |
| TPA | Terephthalic acid |
| UNEP | United Nations Environmental Programme |

# 01 Introduction

# 01 INTRODUCTION

## 1.1 BACKGROUND

Single use plastics has become an important part of modern society. UN Environment Programme (UNEP) defined it as "an umbrella term for different types of products that are typically used once before being thrown away or recycled", which includes food packaging, bottles, straws, containers, cups, cutlery and shopping bags (UNEP 2018a, 2018b).

It has been estimated that about 100-150 million tonnes of plastics are produced for single use purposes and about 8 million tonnes of plastics are dumped into the oceans every year (Plastics Oceans 2019, UNEP 2018a). Moreover, the amount of waste consisting of disposable articles is increasing (Youhanan et al. 2019). The production and disposal of single-use plastics leads to negative consequences to the environment such as impact on the climate, use of non-renewable resources and impacts of littering.

Plastics is used for producing some of the most common types of beverage bottles. It has been estimated that about one million plastic bottles are sold globally every minute (Plastic Soup Foundation, 2020). The environmental impact of single-use plastic bottles has been widely discussed in society. For example, they are among the top single-use plastic products that have been found on beaches (DIRECTIVE (EU) 2019/904, 2019).

There is a need to consider alternative solutions to single-use plastic bottles used in the beverage industry. Resolution 9 of the fourth edition of the United Nations Environment Assembly (UNEA4) in March 2019, on "Addressing Single-use plastic products pollution" (UNEP/EA.4/R.9), "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" (UNEP, 2019). UN Environment Programme was requested by UNEP/EA.4/R.9 to make available existing information on the full life cycle environmental impacts of plastic products compared to products of alternative materials.

Life cycle assessment (LCA) is the tool mainly used for comparing the environmental impact of products. LCA is a standardised method (ISO 2006a, 2006b) quantifying 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. LCA has certain challenges, such as consideration of the complexity of environmental issues and systems perspectives and the lack of standardised assessment methods for, for example, littering of marine and terrestrial ecosystems. Morever, there is sometimes a lack of harmonisation between LCA studies, which sometimes leads to seemingly contradicting results. Due to these complexities, it is essential with expert guidance on the interpretation of LCA studies to understand the environmental impacts of single-use plastic products.

Although the first LCA was performed more than 50 years ago, which actually compared PET beverage bottles to their alternatives made of glass, numerous challenges still remain in terms of comparing plastics and their alternatives (Gomes et al. 2019). Guided by the UNEA4 resolution on "Addressing Single-use plastic products pollution" (UNEP/EA.4/R.9), 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. To provide insight in a comprehensive manner, this study uses the example of single-use plastic bottles used for beverages. This study is a part of a series of reports on single use plastic products. Other products are single-use plastic bags (UNEP. 2020) and food take-away packaging (that will follow in this study series).

It has been estimated that about 100-150 million tonnes of plastics are produced for single use purposes and about 8 million tonnes of plastics are dumped into the oceans every year.

(Plastics Oceans 2019, UNEP 2018a)

## 1.2 PURPOSE, SCOPE AND METHOD

This report aims to provide insights on how LCA can inform decisions on single-use plastic beverage bottles and their alternatives. The study considers alternatives to single-use plastic bottles, that could potentially replace them. Thus they should provide the same function of beverage storage and transportation. The following alternatives are considered: glass bottle (single-use), aluminium can (single-use), carton laminated packaging systems (single-use), reusable steel and aluminium bottles, as well as non-container means for providing drinking water (see table below). Reusable glass bottles were considered in one study only as part of sensitivity analysis. Other beverage containers that don't provide the same function for beverage storage and transportation (such as cups, for instance) are excluded from the study.

As LCA data are already available for this product category, the report is based on the review and analysis (meta-analysis) of selected existing LCA studies that compare plastic bottles and their alternatives. Potentially relevant studies were identified together with UNEP and the Technical Advisory Committee (TAC) in a joint iterative process, as well as from literature search on IVL's internal library, Google and Google Scholar in line with the scope of the report. The further selection was based on the following criteria:

- **Types of bottles:** Bottles used for the most common non-alcoholic beverages (water, soft drinks, juice and milk) were included. Studies of single-use bottles used for other purposes (e.g., soups, olive oil, wine) were excluded.
- **Timeframe of studies reviewed:** Studies published between 2010 and 2020 were considered. This is to account for the fact that production technologies and processes evolve over time, including a potential change in their environmental impact.
- **Transparency:** Studies of sufficient transparency – in terms of possibility to access the underlying data and/or the detailed methodology used in the alaysis – were considered, as this is necessary to interpret the robustness of results and understand what knowledge can be gained from the study.
- **Geographical coverage:** The report is intended to be used globally and the reviewed studies cover this global range to the extent possible. This does not mean that the individual studies have a global or even broad geographical representativeness, but that as a group they should have a broad geographical coverage.
- **Language:** The report mainly focused on studies published in English.
- **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.

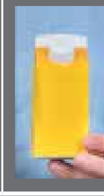
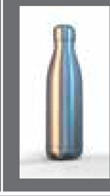
Compliance to international standards, such as ISO 14044:2006, was not used as a selection criterion as the project does not aim at assessing the compliance of studies but rather at explaining their results and extracting the knowledge that can be obtained from them. Further, note that the meta-analysis focuses on solutions for providing beverages to the consumer, whereas the impact of beverage production is not considered.

Seven studies fulfilled the criteria and were selected for the meta-analysiss, see Table 1. These studies can be clustered as follows.

- LCA studies comparing different types of single-use plastic bottles (Section 2.1).
- LCA studies comparing single-use plastic bottles with beverage containers made of other materials (Section 2.2).
- LCA studies comparing single-use plastic bottles and non-container means of providing drinking water (Section 2.3).

No LCA studies on reusable bottles were found to meet the selection criteria, and therefore no such studies were included in the meta-analysis. The studies found were not peer-reviewed and were either dated( from 2009), or not sufficiently transparent. However, given the relevance of this type of bottles among the alternatives to single-use plastic bottles, the challenges and potential benefits of reusable steel and aluminium bottles are briefly discussed in Chapter 2 and 3 based on the studies found.

**TABLE 1: Studies included in the meta-analysis**

| Type of material / Publication | Plastic (single-use) | Glass (single-use) | Alumin-ium (single-use) | Carton laminated (single-use) | Steel, aluminium (reusable) | Non-container means | Geo-graphic scope | Functional unit |
|---|---|---|---|---|---|---|---|---|
| |  |  |  |  |  |  | | |
| **LCA studies comparing different types of single-use plastic bottles** | | | | | | | | |
| Virgin, recycled, and bio-based PET bottles (Benavides et al. 2018) | PET from fossil fuels, biomass, recycled plastic | | | | | | USA | 0.5 l PET bottle |
| Fossil and bio-based PET bottles (Chen et al. 2016) | PET from fossil fuels and biomass | | | | | | USA | 1 kg of PET bottles (equals the weight of approximately 100 bottles with 0.5 l capacity) |
| PLA and PET drinking water bottles (Papong et al. 2014) | PET, PLA | | | | | | Thailand | 1000 units of 0.25 l drinking water bottles |
| **LCA studies comparing single-use plastic bottles with beverage containers made of other materials** | | | | | | | | |
| PET, HDPE, PP, glass and carton packaging systems (Schlecht et al. 2019) | PET, HDPE | | | | | | Denmark, Finland, Norway and Sweden | 1000 l packaging volume for chilled or ambient beverage at the point of sale |
| PET, HDPE, PP, glass and carton packaging systems (Schlecht et al. 2018) | PET, HDPE, PP | | | | | | Belgium, Ireland, the Nether-lands and the UK | 1000 l packaging volume for chilled or ambient beverage at the point of sale |
| Glass bottles, aluminium cans and PET bottles (Amienyo et al. 2013) | | reuse is studied in sensitivity analysis | | | | | the UK | 1 l of a carbonated drink |
| Reusable steel or aluminium bottles (non peer-reviewed) | | | | | | | N/A | NA |
| **LCA studies comparing single-use plastic bottles and non-container means for providing drinking water** | | | | | | | | |
| PET bottles and non-container means for providing drinking water (Garcia-Suarez et al, 2019) | | | | | | | India | 20.000 l of drinking water at consumer's home |

Peer-reviewed publications (included in meta-analysis)   Non peer-reviewed publications (discussed but not included in meta-analysis)

## 1.3 LCA METHOD IN BRIEF

Life Cycle Assessment (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 product life cycle under investigation – or consequential LCA, which has a wider perspective and also includes processes outside the immediate product system that are affected by a change in the supply/demand of the product. Functional unit, level of detail, impact categories (e.g., climate change, acidification, eutrophication), 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. 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.

Life Cycle Assessment (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).

# 02 Meta-analysis of the LCA studies

This chapter presents the main findings and results of the analysed LCA studies. They are grouped in three clusters:

- LCA studies comparing different types of single-use plastic bottles (Section 2.1).
- LCA studies comparing single-use plastic bottles and beverage containers made of other materials (Section 2.2).
- LCA studies comparing single-use plastic bottles and non-container means of providing drinking water (Section 2.3).

Apart from a short description and summary of the results, most information for each study is presented in tables, where the main LCA methodological choices are described.

The row "Material" in the tables refer to the material of the studied packaging product (i.e., bottle, can, pouche or carton packaging).

A standardised color-coding is used in the tables to visualise the comparative impact/ performance of each packaging product analysed (Figure 1). These are indicative and more detailed information should be checked in the individual studies.

Figure 1. Color-coding for the impact indicators.

**Best**

**In-between**

**Worst**

It should be noted that each study has a different scope and level of details. For example, results may be displayed in terms of absolute numbers, percentages or illustrated in figures. Thus, the descriptions of the studies vary: some descriptions contain more detailed information about the results (e.g., specific percentages), while others more general observations (e.g., ranking of compared alternatives).

## 2.1 LCA STUDIES COMPARING DIFFERENT TYPES OF SINGLE-USE PLASTIC BOTTLES

### 2.1.1 Virgin, recycled, and bio-based PET bottles (Benavides et al. 2018)

This study compares the environmental impact of seven ways of producing 500 ml PET bottles, reflecting different combinations of producing two common building blocks of PET: terephthalic acid (TPA) and ethylene glycol (EG). Different scenarios use virgin fossil-based, virgin bio-based and/or fossil recycled resources to produce TPA and EG. In case of bio-based TPA production, two routes are studied: direct fermentation of sugars (a less mature production route, called TPA1) or production from an isobutanol intermediate (TPA2). The seven scenarios are as follows (see further details in Table 2):

- 100% fossil-based PET, i.e., both TPA and EG from virgin fossil resources.
- 100% bio-based PET, with TPA produced via the TPA1 route.
- 100% bio-based PET, with TPA produced via the TPA2 route.
- 65% fossil-based (TPA), 35% bio-based (EG) resources.
- 65% bio-based (TPA1), 35% recycled (EG) resources.
- 65% bio-based (TPA2), 35% recycled (EG) resources.
- 65% virgin fossil-based (TPA), 35% recycled fossil-based (EG) resources.

#### Summary of results and conclusions:

- Bottles with some amount of bio-based and/or recycled content cause lower fossil fuel consumption and climate impact compared to the 100% fossil-based counterpart: from 13% (100% bio-based PET, TPA1) to 59% (65% bio-based (TPA2), 35% recycled PET) fossil fuel consumption, and from 12% (35% bio-based, 65% fossil-based) to 82% (100% bio-based PET, TPA2) lower climate impact. Results for fossil fuel consumption and climate impact do not fully align mainly due to the different credits assigned to biogenic carbon storage, which is present in the five scenarios involving bio-based resources.
- The two 100% bio-based PET bottles cause 22% and 82% lower impact, respectively, compared to the 100% fossil-based bottle. The TPA1 route causes the lower impact reduction (22%), partly due to it being a less mature technology – Benavides and colleagues emphasise that its performance can improve.
- PET bottles made partially (35% of the PET) from recycled content cause between 20% and 73% lower climate impact compared the 100% virgin fossil-based bottle. The bottles combining bio-based (65% of the PET) and recycled content reduce climate impact more compared to the 100% fossil-based PET bottle (35% and 73%, respectively[1]), than what the bottle combining fossil-based (65% of the PET) and recycled content does, which is consistent with the comparison of 100% bio-based and 100% fossil PET. In other words, the results of Benavides et al. (2018) suggest that the more of the virgin fossil-based PET that can be replaced with bio-based and/or recycled materials, the lower the fossil fuel consumption and climate impact.
- The results for water consumption exhibit a very different pattern compared to that for climate impact and fossil fuel consumption: 100% fossil-based PET (100% virgin or 65% virgin/35% recycled) have the lowest impact, whereas all fully or partially bio-based alternatives have between 152% to 489% higher water consumption. The 100% bio-based (TPA1) bottle has the highest water consumption, and bottles with 65% bio-based and 35% recycled PET have lower impact compared to the 100% bio-based counterparts. In other words, the results of Benavides et al. (2018) suggest that bio-based PET bottles cause higher water consumption than what fossil-based PET bottles do, and that using recycled PE reduces water consumption compared to using virgin PET.
- The comparison across the studied impact indicators reveals a clear trade-off: bio-based PET bottles replacing fossil-based PET bottles reduce climate impact and fossil fuel consumption while increasing water consumption. Note that land-use related impacts were not considered – these would likely also be higher for bio-based PET bottles than for fossil-based ones.

1 *This difference is partly due to the TPA1 route being less mature, as was described in the previous bullet point.*

**TABLE 2: Summary table for products considered in the study: bottles made of virgin fossil, recycled fossil, and/or virgin bio-based PET (Benavides et al. 2018).**

| | | PRODUCTS CONSIDERED IN STUDY | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | PET bottle | | | | | | |
| STUDY SCOPE | Material | 100 fossil-based PET | 100% bio-based PET (TPA1) | 100% bio-based PET (TPA2) | 65% fossil- and 35% bio -based PET | 65% bio-based (TPA1) and 35% recycled PET | 65% bio-based (TPA2) and 35% recycled PET | 65% fossil-based and 35% recycled PET |
| | Functional unit | one 0.5 l PET bottle | | | | | | |
| | Capacity (ml) | 500 | | | | | | |
| | Number of uses | 1 | | | | | | |
| | Weight per container (g) | 26 | | | | | | |
| | Geographic region | US | | | | | | |
| | Lifecycle stages | Claims to be cradle-to-grave, but due to excluded processes and due to end-of -life assumptions this is equivalent to cradle-to-gate (if biogenic $CO_2$ captured when growing biomass is assumed to translate to negative GWP results). | | | | | | |
| | End of life assumptions | Landfilling. Assumption of all carbon being stored for 100 years and thus fossil carbon is assumed not to contribute to GWP100 results, and biogenic carbon assumed to translate to negative. Other end-of-life processes, e.g. transportation to landfill, appear to be excluded. | | | | | | |
| IMPACT INDICATORS | Climate change | | | | | | | |
| | Fossil fuel consumption | | | | | | | |
| | Water consumption | | | | | | | |
| Other comments | | It is unclear whether “water consumption” is indeed consumptive water use, i.e. water withdrawn from a water basin. | | | | | | |
| | | The study is said to be cradle-to-grave, but as all processes after gate of bottle production are excluded except landfilling, which is set as zero for all indicators, the results are identical to those expected with a cradle-to-gate scope. | | | | | | |

## 2.1.2 Fossil and bio-based PET bottles (Chen et al. 2016)

This study presents a novel process for producing partially and fully bio-based PET using lignocellulosic biomass from forest residues, and an LCA evaluating the environmental performance of 1 kg bottles[2] made from such PET compared to that of bottles made from 100% fossil-based PET, and to that of partially or fully bio-based PET made from other resources (Table 3).

### Summary of results and conclusions:

- The choice to include or exclude avoided impacts (which are described in Table 3) considerably influences results[3].
  - If avoided impacts are excluded, fully or partially bio-based PET bottles perform worse than 100% fossil-based PET bottles in all impact categories except resource depletion.
  - If avoided impacts are included, 100% bio-based bottles made of TPA from wood and EG from corn or wheat straw perform best in two impact categories (climate impact and fossil resource depletion), and partially bio-based bottles (wood-based TPA, fossil-based EG) perform best in terms of human health impact. In the remaining five impact categories, 100% fossil bottles outperform the fully or partially bio-based counterparts.

2 *Chen and colleagues say 1 kg corresponds to about one hundred 0.5 litre bottles, but they do not specify whether this is the actual capacity of the studied bottles. In the context of the study, in which the focus is on the production routes and resources used to produce the PET material, the capacity of the bottles is, however, of limited importance.*

3 *It can be argued that avoided impacts should be included in studies supporting policy making, as is further discussed in Section 3.2.*

- Results for human health impact, smog creation and acidification are highly influenced by whether or not credits are assigned to the studied system for presumably avoided impact. More specifically, if forest residues would not be used to produce bio-based PET, they could instead be burned (so called slash pile burning) which would contribute considerably to human health impact, smog creation and acidification. To what extent such impact is indeed avoided is, by Chen and colleagues, recognised to vary between different geographical areas, types of woody biomass, and forestry logistics (other reasons for considering or not considering avoided impacts are dicussed in Section 3.2).
- Due to the importance of avoided impact of slash pile burning, PET from woody biomass is generally more influenced by whether or not avoided impacts are considered compared to the other PET alternatives.
- Climate impact results are also highly influenced by whether avoided impacts are considered. Results for wood-based PET bottles and the other bio-based PET bottles are influenced to roughly the same extent.
- Comparisons across the studied indicators reveal trade-offs between impact categories: bio-based PET bottles, particularly those based on forest residues, replacing fossil-based PET bottles can (if avoided impacts are accounted for) reduce climate impact and contributions to fossil resource depletion, while increasing several other environmental impacts.
- Results reveal large differences between bottles of different bio-based feedstocks. For example, wood-based PTA is for most impact categories preferable over corn stover-based PTA, regardless of whether or not avoided impacts are considered. The choice of EG feedstock is less important for results, mainly because it constitutes a smaller share of the PET (made from about 70% TPA and 30% EG).
- The drawbacks of bio-based PET are largely due to extra energy used for agricultural operations and/or production of chemicals used. Improvements are anticipated to be possible by optimization of biorefinery processes.

## TABLE 3: Summary table for products considered in the study: bottles made of fossil and/or bio-based (Chen et al. 2016).

| | | PRODUCTS CONSIDERED IN STUDY | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | PET bottle | | | | | | | | | | | |
| STUDY SCOPE | Material | 100% fossil-based PET | 70% fossil-based/ 30% bio-based (corn) PET | 70% fossil-based/ 30% bio-based (switch-grass) PET | 70% fossil-based/ 30% bio-based (wheat-straw) PET | 30% fossil-based/ 70% bio-based (wood) PET | 100% bio-based PET (70% wood, 30% corn) | 100% bio-based PET (70% wood, 30% switch-grass) | 100% bio-based PET (70% wood, 30% wheat-straw) | 30% fossil-based/ 70% bio-based (corn stover) PET | 100% bio-based PET (70% corn stover, 30% corn) | 100% bio-based PET (70% corn stover, 30% switch grass) | 100% bio-based PET (70% corn stover, 30% wheat-straw |
| | Functional unit | 1 kg PET bottles (corresponds to about one hundred 500 ml bottles) | | | | | | | | | | | |
| | Capacity (ml) | Not specified | | | | | | | | | | | |
| | Number of uses | N/A | | | | | | | | | | | |
| | Weight per container (g) | Not specified | | | | | | | | | | | |
| | Geographic region | US | | | | | | | | | | | |
| | Life cycle stages | Cradle-to-gate | | | | | | | | | | | |
| | End of life assumptions | End-of-life-excluded | | | | | | | | | | | |
| IMPACT INDICATORS (relative results interpreted from figure) | Climate change (without avoided impacts) | | | | | | | | | | | | |
| | Climate change (with avoided impacts) | | | | | | | | | | | | |
| | Fossil resource depletion (without avoided impacts) | | | | | | | | | | | | |
| | Fossil resource depletion (with avoided impacts) | | | | | | | | | | | | |
| | Acidification (without avoided impacts) | | | | | | | | | | | | |
| | Acidification (with avoided impacts) | | | | | | | | | | | | |
| | Terrestrial eutrophication (without avoided impacts) | | | | | | | | | | | | |
| | Terrestrial eutrophication (with avoided impacts) | | | | | | | | | | | | |
| | Human health particulate (without avoided impacts) | | | | | | | | | | | | |
| | Human health particulate (with avoided impacts) | | | | | | | | | | | | |
| | Ecotoxicty (without avoided impacts) | | | | | | | | | | | | |
| | Ecotoxicty (with avoided impacts) | | | | | | | | | | | | |
| | Smog (without avoided impacts) | | | | | | | | | | | | |
| | Smog (with avoided impacts) | | | | | | | | | | | | |
| | Ozone depletion (without avoided impacts) | | | | | | | | | | | | |
| | Ozone depletion (with avoided impacts) | | | | | | | | | | | | |
| Other comments | | Avoided impact includes: 1. Avoided impact from slash pile burning of forest residues, in scenarios with wood feedstock. 2 Avoided impacts from selling excess electricity produced (assumed to displace US average electricity supply) when utilizing fermented lignin residues, in scenarios with bio-based feedstock. 3. Avoided product on from non-energy co-products (production of corn grain, soybean meal is assumed to be displaced and urea), in scenarios with corn feedstocks. 4. Carbon storage credits for biobased bottles. | | | | | | | | | | | |
| | | Chen et al. (2016) recognize other potential benefits of using forest residues as feedstock, e.g. that removal of forest residues from the forest floor reduce fire hazards. Such potential benefits are, however, not quantified in the study. | | | | | | | | | | | |

### 2.1.3 PLA and PET drinking water bottles (Papong et al. 2014)

This study aims to improve the knowledge of the environmental impact of one kind of bio-based plastics produced in Thailand, PLA from cassava roots, and give recommendations of how production can be improved and what end-of-life options are preferable. This is done by an LCA of one thousand 0.25 litre bottles made of either PLA or PET, with three scenarios of PLA production: a base case and two scenarios with improvement options (Table 4). The study analyses also seven end-of-life scenarios for PLA bottles and three end-of-life scenarios for PET bottles (Table 5). The comparisons between scenarios are done with different system boundaries and indicators, as seen in below tables.

#### Summary of results and conclusions:

- Comparing production of PLA and PET bottles reveal a trade-off between impact categories: PLA bottles cause lower climate impact, fossil energy use and human toxicity impact, but higher acidification and eutrophication impact.
- In terms of cradle-to-gate climate impact, what happens at end-of-life is very important both for the absolute results of, and the comparison between, PLA and PET bottles. With landfilling without energy recovery, the impact of PLA bottles can, compared to the best end-of-life option, increase by about 200% – this is because of methane emissions arising in the degradation of PLA (here, worst-case assumptions were made). This scenario also makes PLA bottles about 30-100% worse climate-wise than PET bottles. With incineration with energy recovery, the impact of PET bottles can, compared to the best end-of-life option, increase by about 50% – this is because of the $CO_2$ emissions from incinerating the fossil-derived carbon in the PET bottles.
- In addition to scenarios and results presented in the below tables, the study also shows cradle-to-grave results for one indicator, climate impact, for any combinations of production and end-of-life options, resulting in 21 PLA scenarios and 3 PET scenarios. These results indicate that (i) PLA bottles landfilled at end-of-life, without energy recovery, cause the highest climate impact, followed by PET bottles incinerated at end-of-life, with energy recovery, and (ii) PLA bottles subject to certain production improvements, which at end-of-life are incinerated with energy recovery, cause the lowest climate impact, followed by PLA subject to lesser or no production improvements, which are incinerated with energy recovery.

**TABLE 4: Summary table for products considered in the study: PLA and PET bottles (Papong et al. 2014).**

| | | PRODUCTS CONSIDERED IN STUDY | | | |
|---|---|---|---|---|---|
| | | PLA bottle (base case) | PLA bottle (improved, option 1) | PLA bottle (improved, option 2) | PET bottle |
| STUDY SCOPE | Material | Bio-based PLA (Cassava) | | | Fossil-based PET |
| | Functional unit | one thousand 0.25 l bottles | | | |
| | Capacity (ml) | 250 | | | |
| | Number of uses | Not specified | | | |
| | Weight per container (g) | Not specified | | | |
| | Geographic region | Thailand | | | |
| | Lifecycle stages | Cradle-to-gate (end-of-life presented separately, see separate table) | | | |
| | End of life assumptions | Excluded (but separately presented, see separate table) | | | |
| IMPACT INDICATORS | Climate change | | | | |
| | Fossil energy demand | | | | |
| | Acidification | | | | |
| | Eutrophication | | | | |
| | Human toxicity | | | | |

**TABLE 5: Summary table for products considered in the study: seven end-of-life scenarios for PLA bottles and three end-of-life scenarios for PET bottles (Papong et al. 2014).**

| | | PRODUCTS CONSIDERED IN STUDY | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | PLA bottle | | | | | | | PET bottle | | |
| STUDY SCOPE | Material | Bio-based PLA (Cassava) | | | | | | | Fossil-based PET | | |
| | Functional unit | one thousand 0.250 l bottles | | | | | | | | | |
| | Capacity (ml) | 250 | | | | | | | | | |
| | Number of uses | Not specified | | | | | | | | | |
| | Weight per container (g) | Not specified | | | | | | | | | |
| | Geographic region | Thailand | | | | | | | | | |
| | Lifecycle stages | End-of-life (cradle-to-gate presented separately, see separate table) | | | | | | | | | |
| | End of life assumptions | Com-posting | Incin-eration with energy recovery | Landfill without energy recovery | Landfill with energy recovery | Chem-ical re-cycling | 80% com-posting +20% landfill with energy recovery | 80% com-posting +20% incin-eration with energy recovery | Landfill | Re-cycling | Incin-eration with energy recovery |
| IMPACT INDICATORS | Climate change | | | | | | | | | | |
| | Fossil energy demand | | | | | | | | | | |
| Other comments | | In PLA landfilling, a worst-case scenario is assumed in terms of the generation of methane due to anaerobic degradation of PLA, and this 60% of the methane released is recovered and used to produce energy, whereas 40% is lost to the atmosphere. In PET landfilling, 1% of carbon is assumed to be degraded during a 100-year time period, and this is (according to our interpretation) assumed to be released as CO. Apart from waste treatment processes, the end of life stage also includes collection of used bottles-this is assumed to be constant between scenarios and its contribution is negligible compared to other processes. All energy and material recovered at end of life are assumed to replace corresponding average energy and material production on the market. Uptake and emissions of biogenic CO2 in the PLA life cycle are not accounted for, based on the assumption that uptake equals emissions and thus are (presumably) climate neutral. | | | | | | | | | |

## 2.2 LCA STUDIES COMPARING SINGLE-USE PLASTIC BOTTLES WITH BEVERAGE CONTAINERS MADE OF OTHER MATERIALS

### 2.2.1 PET, HDPE, PP, glass and carton packaging systems (Schlecht et al. 2018, 2019)

The study by Schlecht et al. (2018) analyses the life cycle environmental performance of beverage carton packaging systems and their alternatives on four individual markets in Northwest Europe: Belgium, Ireland, the Netherlands and the United Kingdom. The study by Schlecht et al. (2019) makes a similar analysis but considers another market in the Nordic countries: Denmark, Finland, Norway and Sweden. The main objectives of these studies are to provide knowledge on the environmental strengths and weaknesses of carton packaging systems and compare the environmental performance of those cartons with the competing packaging system in the mentioned above markets.

The following types of packaging systems are included in both studies: PET bottles, HDPE bottles, glass bottles, PP containers with aluminium closures[4], stand up pouches, "Grab and Go"[5] and several types of carton packaging systems (Table 6). Carton packaging systems are assumed to consist of the following main materials: composite (liquid packaging board, plastics, aluminium), closure (plastics). Different types of carton packaging systems included either fossil-based plastics or bio-based PE.

The studies include different types of packaging per different segments, which are grouped per type of beverage (i.e., milk, water, juice), temperature of the drink (ambient or chilled) and packaging volume. This means that depending on the type of segment considered, different types of materials might be used in order to provide the same function. For instance, bottles for water might be different in terms material composition in comparison with beverage containers used for dairy products

**Summary of results and conclusions:**

- Carton packaging systems with fossil-based plastics can be environmentally prefered for most segments, except for bottles used for the segment of still water, where no unambiguous conclusion can be drawn. PET bottles seem to have a similar environmental performance compared to carton packaging systems in the segment of still water. A reason for this is that PET bottles used for still water are more lightweight and contain no barrier materials, while beverage cartons used for still water mostly contain an aluminium barrier layer.

- In comparison with fossil-based material used for the production of carton packaging systems, the use of bio-PE leads to lower climate impact, but higher impact in terms of other impact categories.

- In comparison with carton packaging systems, glass bottles showed worse environmental performance in all the impact categories except aquatic eutrophication and use of nature (an impact category reflecting the integration of impacts on land use and biodiversity) (Schlecht et al. 2018).

- The closures (which are made of plastics) and barrier materials (mainly made of aluminium) play a significant role in the life cycle impact of the carton packaging systems. Thus it is important to consider smaller and lighter closures, as well as investigating other types of materials that could substitute aluminium as a barrier.

4 *PP containers with aluminium closures used for dairy products (included only in the study by Schlecht et al. (2018)).*
5 *Small bottles (with volumes 0.25 l to 0.38 l).*

**TABLE 6: Summary table for products considered in the study: PET, HDPE, PP, glass and carton packaging systems (Schlecht et al. 2018, 2019).**

| | | PRODUCTS CONSIDERED IN STUDY | | | | | |
|---|---|---|---|---|---|---|---|
| | | PET bottle | HDPE bottle | Glass bottle | PP container with aluminium closure | Stand-up pouches | Carton packaging system |
| STUDY SCOPE | Material | Virgin PET, recycled PET (11.7%), TiO2 (1.6%), Carbon Black (5%), PP | HDPE, LDPE, Aluminium | glass, paper, HDPE, PET, tin plate | PP, TiO2 (1.6%), aluminium | Virgin PET, HDPE, Aluminium | Composite (liquid packaging board, LDPE, Bio-PE, Aluminium), closure (HDPE, LDPE, Bio-PE, PP) |
| | Functional unit | 1000 l packaging volume for chilled or ambient beverage at the point of sale | | | | | |
| | Capacity (ml) | Different volumes were analysed ranging from 200 ml to 2000 ml (depending on the type of beverage and country) | | | | | |
| | Number of uses | 1 | 1 | 1 | 1 | 1 | 1 |
| | Weight per container (g) | depending on volume and country | depending on volume and country | depending on volume and country | 17,56 | 3,79 | depending on volume and country |
| | Geographic region | Belgium, Ireland, the Netherlands and the United Kingdom (Schlecht et al, 2018) and Denmark, Finland, Norway and Sweden (Schlecht et al, 2019) | | | | | |
| | Lifecycle stages | Cradle-to-grave (excluding processes that are the same for all types of packaging: for instance, production of beverage, use phase etc.) | | | | | |
| | End of life assumptions | Country-specific waste management scenario (including recycling, landfilling and incineration) | | | | | |
| IMPACT INDICATORS | Use of nature<br>Water use<br>Photo-oxidant formation<br>Acidification<br>Aquatic eutrophication<br>Terrestrial eutrophication<br>Climate change<br>Particulate matter<br>Ozone layer depletion potential<br>Primary energy demand<br>Non-renewable primary energy | • Different types of packaging were only compared within one type of segment (considering the type of beverage, volume and country).<br>• The results of the study showed that each packaging system shows different environmental performance depending on the market and segment it is used for.<br>• Beverage cartons with fossil based plastics show lower environmental impacts than their compared alternative packaging systems in almost all segments within the studied markets in most.<br>• No general advantage of beverage cartons can be seen in the segment of still water, where there are no big differences observed with PET bottles.<br>• The use of bio-based PE in the carton packaging systems leads to lower impact on climate change, but increases the environmental impacts in all the other impact categories. | | | | | |
| Other comments | | • The study includes and showes separately credits for material recycling, credits for energy recovery (replacing e.g. grid electricity) and credits for uptake of athmospheric CO2 during the plant growth phase.<br>• Sensitivity analysis is performed for the following parameters: system allocation, bio-based plastics in HDPE bottles, recycled content in PET and HDPE bottles, plastic bottle weight and alternative barrier material in beverage cartons in different segments. | | | | | |

### 2.2.2 Glass bottles, aluminium cans and PET bottles (Amienyo et al. 2013)

This study aims to present "the full life cycle impacts of carbonated soft drinks manufactured and consumed in the UK, as well as the related impacts at the sectoral level." The study compares three types of packaging used for carbonated drinks: glass bottles (0.75 l), aluminium cans (0.33 l) and polyethylene terephthalate (PET) bottles of two capacities: 2 litre and 0.5 litre (Table 7). Two types of functional units are considered: 1 litre of packaged drink and total annual production and consumption of carbonated drinks in the UK (sectoral level). Due to the scope of the meta-analysis, only the results for the first type of functional unit are considered.

It should be noted that this study compares the bottles of different capacities. They cannot be always compared directly since they deliver different functionalities. For instance, the bottle of 0.5 litre can be used for one serving as take away, which cannot be done with the 2 litre bottles.

#### Summary of results and conclusions:

- Single use glass bottle (0.75 l) is the worst option for all environmental categoreis except for eutrophication and freshwater aquatic ecotoxicity.
- The study considers that glass bottles are used only once and then recycled. However, reuse of glass bottles was modelled as part of sensitivity analysis. Modelling reuse of glass bottles, the study took into account such activities such as transportation, de-palletising, de-crating, de-capping, washing and inspecting the bottles during each reuse cycle. The study concludes that glass bottles need to be reused at least three times to be environmentally comparable with aluminium cans and 0.5 litre PET bottles. However, the study did not discuss the average rate for reuse of glass bottles in the region.
- PET bottles (2 l) have the best environmental performance, except for eutrophication, ozone layer depletion and terrestrial ecotoxicity potential, where aluminium cans show better results.
- The volume of bottles is more important than the material: 2 litre PET bottles have less environmental impact per litre of carbonated drink than 0.5 litre PET bottles. For instance, in terms of freshwater aquatic ecotoxicity, the study shows that 0.5 litre PET bottles are the worst, while 2 litre PET bottles are the best alternative, when comparing with glass bottles and aluminium cans (Table 7).
- Increasing recycling of PET bottles to 60% reduces climate impact of the carbonated drink by half compared to the current recycling rate (24%).
- The study includes transportation of bottles and concludes that the contribution of transport is small—between 1.4 % for glass bottles and 3.4 % for 2 l PET bottles. Thus there is a minor difference in the impacts from transportation between different types of bottles.
- Impact on GWP of refrigerated storage at retailer is studied with the help of sensitivity analysis on the example of aluminium cans and 0.5 l PET bottles. Comparing aluminium cans and PET bottles, it can be also concluded that refrigerated storage in aluminium can contributes to higher GWP than regrigerated storage for PET bottles. It is concluded that refrigerated storage adds 33 % to the total GWP of the drink for the aluminium cans and 24.5 % for the PET bottles. This makes the refrigerated storage the second largest contributie to the GWP of the drink (after packaging production) for both types of beverage containers. Thus the study suggested to avoid erfrigerated storage at retailer as much as possible.

Comparing aluminium cans and PET bottles, it can be also concluded that refrigerated storage in aluminium can contributes to higher GWP than regrigerated storage for PET bottles.

**TABLE 7: Summary table for products considered in the study: glass bottles, aluminium cans and PET bottles (Amienyo et al. 2013)**

| | | PRODUCTS CONSIDERED IN STUDY | | | |
|---|---|---|---|---|---|
| | | Glass bottle | Aluminium can | PET bottle (0.5 l) | PET bottle (2 l) |
| STUDY SCOPE | Material | Bottle body-glass (35% recycled content), top (84 % virgin aluminium alloy and 16 % LDPE), label- kraftpaper | Can body (48 % recycled aluminium), Can ends (100 % virgin aluminium) | Bottle body (virgin PET) Top (virgin HDPE) Label (virgin PP) | Bottle body (virgin PET) Top (virgin HDPE) Label (virgin PP) |
| | Functional unit | 1 l of a carbonated drink | | | |
| | Capacity (ml) | 750 | 330 | 500 | 2000 |
| | Number of uses | 1 (reuse of 2-25 times was included in sensitivity analysis) | 1 | 1 | 1 |
| | Weight per container** (g) | 600 | 13 | 27 | 47 |
| | Geographic region | UK | | | |
| | Lifecycle stages | Cradle-to-grave (includes both production of primary packaging (bottles, cans), secondary packaging (trays, wraps, pallets, etc.) and drinks manufacturing.* | | | |
| | End of life assumptions | Average UK waste management scenario has been assumed | | | |
| IMPACT INDICATORS | Abiotic depletion potential | | | | |
| | Acidification | | | | |
| | Eutrophication | | | | |
| | Freshwater aquatic ecotoxicity potential | | | | |
| | Climate change | | | | |
| | Human toxicity potential | | | | |
| | Marine aquatic ecotoxicity potential | | | | |
| | Ozone layer depletion potential | | | | |
| | Photochemical oxidant creation potential | | | | |
| | Terrestrial ecotoxicity potential | | | | |
| | Primary energy demand | | | | |
| Other comments | | • The study included also the life cycle impacts of drink production. It concluded that packaging has the major contribution to the total GWP (between 49 % (for 2 l PET bottles) and 79 % (for aluminium cans).<br>• Transport of drinks contributes only to 1-7% of the total impacts (depending on transport distance assumed).<br>• Reuse of glass bottles and different recycling rates (40% and 60%) for PET have been tested with sensitivity analysis. | | | |

* This study analyses only the results for packaging (since drinks are excluded from the scope of this study)

**Recalculated based on data provided in the study

### 2.2.3 Studies of reusable steel and aluminium bottles

One of the main beverage-container options missing in the above meta-analysis are reusable bottles, which are increasingly being used and promoted to avoid particularly single-use plastic water bottles (Coelho et al, 2020; UNEP, 2017). Several studies analysing reusable steel and aluminium bottles were found. However they did not meet the inclusion criteria for the meta-analysis (as described in Section 1.2). However main conclusions from those studies are summarised below, to give an indication of what kind of information is available and accessible online concerning the environmentally viability of reusable steel and aluminium bottles.

The master's thesis of Dettore (2009) compares different types of single-use plastic bottles (e.g., from fossil and bio-based resources, from virgin and recycled resources), home and office delivery (HOD)-bottled water (consumed via, e.g., reusable steel bottles), and tap water. Tap water outperforms the alternatives in all impact categories, and the HOD-bottled water reduces energy use, solid waste generation and greenhouse gas emissions compared to single-use water bottles, but makes no difference in terms of water use.

DEQ (2009), a study conducted by Franklin Associates for Oregon State's Department of Environmental Quality, shows strong similarities to Dettore (2009) (who was involved in the study) but is a more extensive report, for example including more impact categories. The study also compares single-use plastic bottles (e.g., from fossil and bio-based resources, from virgin and recycled resources), HOD-bottled water (consumed via, e.g., reusable steel bottles), and tap water, and concludes that tap water outperforms the alternatives in all considered impact categories. However, the authors claim that, based on the results, no conclusion can be drawn on whether HOD-bottled water or single-use water bottles is generally preferable.

Pathwater, a supplier of bottled water sold in reusable aluminium bottles, compare their bottle with single-use plastic bottles and concluded that after three uses it reaches "break even" climate-wise (Pathwater 2018). In other words, if used more than three times their bottle generates lower greenhouse gas emissions compared to single-use plastic bottles (note that the technical life span of reusable aluminium bottles can be expected to be much higher than three uses). Since they claim their bottles are used more than ten times on average, they conclude that the bottles cause lower climate impact compared to single-use plastic bottles. The study also points at a significant share of littering (8%) for plastic bottles (in addition to 67% being "thrown away", presumably disposed of as waste and ending up in landfills and incineration), vs. 1% for the reusable aluminium bottles; the subsequent impacts of such litter once it reaches the environment are not further assessed, though.

The above studies indicate potential environmental benefits of reusable steel and aluminium bottles in comparison to single-use plastic bottles, but that these depend considerably on number of uses and vary between impact categories – for some impact categories the reusable bottles are more certain to reduce impact than for others.

Finally, it shall be noted that above conclusions are uncertain compared to other conclusions discussed in the present study, and further peer-reviewed studies are recommended to explore the environmental viability of steel bottles. The analysis of the studies of reusable steel and aluminium bottles was not as detailed as for the studies included in the meta-analysis, and their inclusion in above discussion should not be interpreted as an endorsement of their quality.

## 2.3 LCA STUDIES COMPARING SINGLE-USE PLASTIC BOTTLES AND NON-CONTAINER MEANS FOR PROVIDING DRINKING WATER

### 2.3.1 PET bottles and non-container means for providing drinking water (Garcia-Suarez et al. 2019)

To fill a knowledge gap in the environmental impact of different options for providing safe drinking water in India, this study compares the potential environmental impacts of tap water boiled in a lidded steel pan heated by liquified petroleum gas (LPG), store-bought bottled water, and tap water purified and desalinated using an in-home reverse-osmosis (RO) device powered by the Indian electricity grid mix (Table 8). A sensitivity analysis tests potentially influential parameters for (i) the RO case: different means of disposal of device and packaging, consumables needed, quantity of electricity use, and device lifetime, and (ii) the bottle case: different means and distances of delivery to the store, weight of bottle, and type of secondary packaging.

**Summary of results and conclusions:**

- Water supplied by bottles is the worst option for all studied impact categories, also considering the fifteen additional impact categories shown in the appendix of the study (not shown in below table).
- For impact results shown in the below table, and comparing baseline scenarios, water supplied by the RO device has 94% (climate change), 83% (freshwater eutrophication), 95% (fossil depletion), 92% (terrestrial acidification), 99% (green water consumption), and 42% (blue water consumption) lower impact than bottled water.
- For impact results shown in the below table, and comparing baseline scenarios, boiled water has 79% (climate change), 97% (freshwater eutrophication), 78% (fossil depletion), 86% (terrestrial acidification), 99% (green water consumption), and 67% (blue water consumption) lower impact than bottled water.
- Although the baseline scenario indicate considerable drawbacks with bottled water compared to the compared non-container options, the baseline bottle scenario is still a conservative one. The sensitivity analysis, which explore scenarios which are less favourable for the bottle, thus reveal even larger benefits of non-container options.
- Whether water supplied by boiling tap water or the RO device is preferable depends on the impact category considered, i.e., in the choice between these alternatives there is a trade-off between environmental impacts.
- Garcia-Suarez and colleagues recognise that (i) the calculated impact of bottled water is likely an underestimation, (ii) there are functional differences between the compared options (boiled water may not be fully comparable to the other options in terms of taste, bottled water may be more convenient to use, e.g., on the move), (iii) non-assessed impacts differ between compared options (e.g., plastic bottles contribute to plastic litter), and (iv) there are other options in India for delivering the studied functional unit, not included in their study, such as subscription to home-delivery of 20 litre plastic bottles which are returnable and reusable.

Whether water supplied by boiling tap water or the RO device is preferable depends on the impact category considered.

**TABLE 8: Summary table for products considered in the study: PET bottles and non-container means for providing drinking water (Garcia-Suarez et al. 2019).**

| | | PRODUCTS CONSIDERED IN STUDY | | |
|---|---|---|---|---|
| | | **Boiled tap water** | **Water in PET bottle** | **Tap water purified with a domestic reverse-osmosis device** |
| STUDY SCOPE | Material | N/A | PET bottle, PP cap | N/A |
| | Functional unit | 20,000 litre of drinking water at consumer's home | | |
| | Capacity (ml) | N/A | 1000 | N/A |
| | Number of uses | N/A | 1 use per bottle | Three scenarios for use phase: one device provides 20 $m^3$ (baseline), 8 $m^3$ or 40 $m^3$ water |
| | Weight per container (g) | N/A | Two scenarios: 18 g (bottle) + 1.4 g (cap) (baseline), 22.4 g (bottle) + 1.6 (cap) | N/A |
| | Geographic region | India | | |
| | Lifecycle stages | Cradle-to-grave | | |
| | End of life assumptions | N/A | Bottle: 4% incineration, 16% landfill, 80% recycling; cap: 15% incineration, 85% landfill. Cut-off allocation. | Three scenarios for disposal of device and packaging: 100% recycled (baseline), 100% landfilled, 100% incinerated. Cut-off allocation. |
| IMPACT INDICATORS | Climate change | | | |
| | Fresh water eutrophication | | | |
| | Fossil depletion | | | |
| | Terrestrial acidification | | | |
| | Green water consumption | | | |
| | Blue water consumption | | | |
| Other comments | | In the boiled water scenario, water is boiled in a lidded steel pan (5 litre) for 1 minute, heated by liquified petroleum gas | | |
| | | The baseline bottle scenario is a conservative scenario. A sensitivity analysis was used to explore alternative scenarios – all these scenarios resulted in higher impact for the bottle. Above relative impact indicator results are therefore valid for also for the alternative scenarios | | |

# 03 Conclusions

# 03 CONCLUSIONS

The below sections are intended for different audiences. Section 3.1 presents a summary of what can be said about the environmental impact of single-use plastic bottles and their alternatives and is intended for all readers. Section 3.2 picks on the main recommendations for LCA practitioners interested in furthering the research on the environmental impacts of single-use plastic bottles and their alternatives. And Section 3.3 extracts some key recommendations to be considered in policy responses to single-use plastic bottles based on the findings of this meta-analysis.

## 3.1 ENVIRONMENTAL IMPACTS OF SINGLE-USE PLASTIC BOTTLES AND THEIR ALTERNATIVES

The below sections present a summary of what can be said about the environmental impacts of bottles for soft drinks, water, milk and juice based on the studies analysed in Section 2.

### 3.1.1 Comparisons of different single-use plastic bottles

The main discussion points and conclusions from reviewing Benavides et al. (2018), Chen et al. (2016) and Papong et al. (2013), which assess and compare different kinds of plastic bottles (bottles from fossil versus bio-based resources, and, in the case of Benavides and colleagues, recycled resources) are:

- There are trade-offs between impact categories when comparing fossil and bio-based plastic bottles. Often, bio-based bottles appear to have benefits in terms of, for example, climate impact and fossil resource use, while they have disadvantages in terms of, for example, water use and eutrophication. There are, however, exceptions, for example due to the choice of allocation method – in particular whether or not various credits (consequential modelling elements) along the life cycle are considered. In Section 2.1.2, one example was given: whether PET bottles made of forest residues are assigned credits from the avoided alternative use of the forest residues, for example slash pile burning. Such credits can, specifically for bio-based bottles, vary substantially between different geographical areas, types of woody biomass, and forestry logistics.

- There are large differences in the environmental impact between different bio-based production routes, for example, due to different feedstocks, processes and level of maturity. For example, environmental impact can depend on whether forest or agricultural resources are used, and what the alternative uses of these resources are. Different ways to produce bio-based TPA, a common building block of PET, provides an example of different levels of maturity: production from an isobutanol intermediate is a more mature production route (with lower environmental impact) compared to direct fermentation of sugars (Benavides et al. 2018). One should be particularly careful when assessing and comparing less mature production routes, and when developing policies affecting such routes.

- Plastic bottles made from recycled content were found to be preferable compared to fossil-based bottles for the studied indicators (Benavides et al. 2018). The comparison between bottles made of recycled and bio-based virgin resources was more mixed (Benavides et al. 2018). In other words, bottles from recycled resources seem to be environmentally preferable compared to bottles from virgin fossil resources, but they are not necessarily environmentally preferable compared to bottles from virgin bio-based resources. The comparison between bio-based bottles and bottles made of recycled content depends on impact category though. For climate impact, bio-based PET can be a preferable material, whereas for water consumption recycled PET seems to be the preferable material (Benavides et al. 2018).

- What happens at end-of-life can considerably influence results in absolute and relative terms (comparisons between alternatives). For example, to what extent methane is generated in landfilling of PLA bottles – a potentially substantial contribution to the overall climate impact of PLA bottles – depends on moisture and temperature, which vary between landfills (Papong et al. 2014). Also, to what extent the generated methane is captured and used for energy purposes, rather than emitted to the atmosphere, varies greatly between landfills (Papong et al. 2014). Similarly, the recycling rate of plastic bottles influences their environmental impact (Amienyo et al., 2013; Schlecht et al., 2019).

- The three studies cover different bottle capacities: 0.5 litre bottles (Benavides et al. 2018), 0.25 litre bottles (Papong et al. 2013), and unspecified size (Chen et al. 2016), and do not specify the type of beverage. This is a sufficient level of detail for the aims of the studies, which focus on comparing plastic bottles made of different resources and produced by different production routes, where the compared materials are more or less identical and functionally equivalent (they are a bit different for Papong et al. (2018), where PLA and PET bottles are compared).

### 3.1.2 Comparisons of single-use plastic bottles and beverage containers made of other materials

The main discussion points and conclusions from reviewing three studies that compare plastic and other alternative types of materials used for the production of beverage containers: plastic, glass and carton (Schlecht et al. 2018, 2019) and glass, plastic and aluminium (Amienyo et al. 2013) are:

#### Single-use plastic bottles vs. cartons

- The studies by Schlecht et al (2018, 2019) are the only studies analysed in this report that compare plastic bottles vs. cartons. They conclude that beverage carton systems with fossil-based plastics[6] are environmentally preferable for most beverage segments (for instance, milk, juices and similar). However, beverage cartons have no advantages in terms of life cycle impact when it comes to their usage as containers for water, where PET bottles show a similar environmental performance as cartons.

- The use of bio-PE in the production of carton packaging systems leads to a better environmental performance in terms of climate change, but worse in terms of other impact categories, as shown in the studies by Schlecht et al. (2018, 2019).

- The studies by Schlecht et al (2018, 2019) compare carton packaging systems and their possible alternatives in the Northwestern Europe, thus more similar studies are needed for other geographical regions, in order to make more general conclusions.

#### Single-use plastic bottles vs. single-use and reusable glass bottles

- Single-use glass bottles (that are used only once) show worse environmental performance than single-use plastic bottles in all impact categories except aquatic eutrophication (Schlecht et al. 2019) and eutrophication and freshwater aquatic ecotoxicity (Amienyo et al. 2013). Based on the sensitivity analysis in Amienyo et al. (2013), glass bottles (0.75 l) need to be reused at least three times to be environmentally equivalent to aluminium cans and PET bottles (0.5 l) .

- In 2016, the German EPA (Detzel et al, 2016) published a report which focuses on describing the process and results of developing minimum life cycle assessment requirements for beverage containers in the context of the German Packaging Directive. In that context, the report also presents the results of LCAs conducted between 1995 and 2010, which are either publicly accessible or are internally available to the German EPA to their full extent. The included studies conclude that reusable glass bottles can be environmentally advantageous in comparison to single-use plastic bottles.

#### Single-use plastic bottles vs. aluminium cans

- Considering the impact per litre of beverage, the results from Amienyo et al. (2013) indicate that, compared to a 0.33 litre aluminium can, a 0.5 litre PET bottle has slightly greater climate impact, while the climate impact of a 2 litre PET bottle is much lower.

- Comparing plastic bottles to aluminium cans, different holding capacities were analysed. They cannot be compared directly due to their different functionalities (as mentioned in Section 2.2.2).

6 *Beverage cartons analysed in the studies by Schlecht et al (2018, 2019) are assumed to consist of the following main materials: composite (liquid packaging board, plastics, Aluminium), closure (plastics). They can contain either fossil-based plastics or bio-PE.*

**Single-use plastic bottles vs. reusable steel and aluminium bottles**

- No peer-reviewed studies were found comparing the environmental impact of reusable steel or aluminium bottles with single-use plastic bottles.
- The non-peer reviewed studies considered, indicate potential environmental benefits of resusable steel/ aluminium bottles in comparison to single-use plastic bottles (Dettore 2009, DEQ 2009, Pathwater 2018).
- For aluminium bottles to have benefits, it is suggested they must be used more than three times – as the technical life span can be expected to be much higher than three times, this indicates substantial potential environmental gains compared to single-use plastic bottles.
- Robustness of the data needs to be further enhanced through peer-reviewed studies to provide more definite conclusions.

### 3.1.3 Comparisons of plastic bottles and non-container means for providing drinking water

See below for main discussion points and conclusions on the comparison of plastic bottles and non-container means for providing drinking water, based on the review of of Garcia-Suarez et al. (2019).

- The study of Garcia-Suarez and colleagues indicate that non-container options (in this case boiled tap water and tap water purified by RO devices) have considerable environmental advantages in all studied impact categories, even when the conservative baseline bottle scenario is considered. For climate change, freshwater eutrophication, terrestrial acidification and fossil depletion, the impact of bottled water is roughly one order-of-magnitude higher than for the non-container options, for green water consumption it is roughly two order-of-magnitudes higher, and for blue water consumption the impact is roughly twice as high.
- Considering that the water is boiled with heat from a fossil fuel in Garcia-Suarez et al. (2019), it can be expected that non-boiled tap water is also environmentally preferable compared to bottled water in geographical contexts where non-boiled tap water is safe to drink.
- Beverage containers and non-container means for providing beverages have very different functionality, and are not be viable options in all contexts. For example, non-container means are not portable. Differences in functionality must be considered when comparing these options. Furthermore, container and non-container means can often be combined, for example, water from a tap (boiled or non-boiled) or a RO device can be used to refill reusable bottles.
- In general, one should be careful in drawing general conclusions based on one study focussed on a specific geographical context (in this case India). However, considering the conservative assumptions done for bottled water in this study, and that, for example, boiled water is assumed to be heated by fossil-based energy, the benefits shown for non-container options can be excepted also for most other geographical contexts. Nevertheless, further studies of non-container means for providing drinking water are recommended.

For aluminium bottles to have benefits, it is suggested they must be used more than three times – as the technical life span can be expected to be much higher than three times, this indicates substantial potential environmental gains compared to single-use plastic bottles.

## 3.2 IMPORTANT ASPECTS IN LIFE CYCLE ASSESSMENTS OF PLASTIC BOTTLES AND THEIR ALTERNATIVES

Based on the analysed LCA studies, several aspects were indentified that should be carefully considered when conducting and interpreting LCAs of plastic bottles and their alternatives. Below is a non-exhaustive list of such aspects. Note that this section does not cover important aspects to consider in policy making, which are instead included in Section 3.3.

- **Container material.** The studies show big differences between container materials. For example, single-use glass bottles showed worse environmental performance in comparison with their alternatives for almost all impact categories, except eutrophication, ozone layer depletion and terrestrial ecotoxicity. Similarly, plastic bottles made from recycled content were found to be preferable compared to fossil-based bottles.

- **Maturity of the technologies and production route.** Single-use plastic bottles may be produced from fossil or bio-based resources, from virgin or recycled resources, which greatly influences their environmental impact. Whether the studied product represents a novel small-scale solution or an established large-scale solution may considerably influence its environmental performance. A new and small-scale solution is more likely to improve in the future, compared to an older established solution – this must be accounted for when interpreting results. For example, production of bio-based plastic bottles is often less mature than production of fossil-based plastics bottles (e.g., see Chen et al. 2016) and therefore one must be catious in making comparisons.

  There are also differences within each of these categories, for example there are many possible bio-based resources causing different environmental impact, and there are several subsequent routes for producing bio-based plastics out of these resources.

  Scenario analysis is recommended to explore potential future environmental impact of less mature technologies.

- The **volume of the beverage container** is an important aspect of its functionality and must be carefully considered when comparing options for providing beverages to consumers. For instance, cartons have been shown to be the best choice in terms of all environmental impact categories for juice packaging of small volumes (i.e., 0.2–0.3 l). On the other hand, when juice packaging of bigger volumes (1 l) is considered, no general advantage was observed for cartons, except for climate impact (Schlecht, 2018). Another example is given by Amienyo et al. (2013), which show that 2 litre PET bottles are environmentally preferable to 0.5 litre PET bottles, because more PET is needed per volume of beverage in the case of smaller bottles.

  Moreover the ratio of leakage and other waste of the beverage is likely to vary depending on the container (and its material and capacity). This will also affect the environmental impact of beverage production, but also the number of containers used and, hence, the environmental impacts of the containers. These factors are not accounted for in the analysed studies, and deserves to be studied further.

- **Functional equivalence** is important when alternative containers or non-container beverage solutions are compared. Compared alternatives should be capable of providing the same beverage, of comparable quality, to the same consumer. For example, not all containers are suitable for all types of drinks: water, soft drinks, juice and milk, chilled drinks or ambient drinks, as analysed by Schlecht et al. (2018, 2019). But even if functions are not identical, comparisons may still be made. For example, as shown by Garcia-Suarez et al. (2019), bottled water and boiled tap water may be compared as options for drinking water as they, in many contexts, provide comparable functions. However, they do have functional differences. For example, water quality and accessibility may differ, which should be considered when interpreting results. Also, alternatives can be combined to different extent. For example, container and non-container means of providing a beverage can often be combined, for example, water from a tap (boiled or non-boiled) or a RO device can be used to refill reusable bottles.

- **Geographical context**, the location of production, use and end-of-life affect technologies used, user behaviour and other aspects, which in turn influences the environmental impact of beverage container systems. For example, typical recycling rates of PET and glass bottles, or of aluminium cans or carton packaging, may differ between countries. For instance, the use of a deposit return system[7] in Sweden leads to considerably higher recycling rates for PET bottles than in many other countries, and Schlecht et al. (2019) show that such higher recycling rates generate lower environmental impact in many impact categories. Similarly, for reusable glass bottles, the number of reuses before breakage may differ between countries.

  Another example of important geographical differences concerns the production of bio-based PET bottles, where the access to different feedstock – forest residues, cassava, corn stover, wheatstraw, switchgrass – may differ between countries and regions, and the use of different resources results in different environmental impacts (Chen et al. 2016, Papong et al. 2014). Also to what extent avoided impacts can be expected in bio-based production systems may depend on geography (Chen et al. 2016).

- **Aim of the study**. A study aimed at mapping the environmental impact of an average plastic bottle in a certain market may be very different from a study aimed at exploring consequences of specific means of reducing the environmental impact of a certain plastic bottle producer. Examples of aspects that may differ depending on a study's aim are: the choice of system boundaries (e.g., whether use and end-of-life is included), selection of datasets (e.g., average or marginal electricity supply), how the environmental impact of multi-functional processes is divided between the functions, and the choice of impact indicators. In the LCA community, these differences are often framed in terms of accounting/attributional LCA (ALCA) and consequential/change-oriented LCA (CLCA). It can be argued that CLCA is more suitable for studies aimed at supporting policy making, as policy making is about implementing changes. A specific modelling aspect that generally is more common in CLCAs is the inclusion of avoided impact occurring outside the immediate product system, but happening as a consequence of product system. Whether to consider these was shown to be of great importance in studies of bio-based plastic bottles (Chen et al. 2016), thus the choice between ALCA and CLCA can be of particular importance in such studies.

  That well-made studies are tailor-made for specific aims is true also for studies intended to be used for policy making. In other words, a study can be of great value for the development of a specific policy if it is designed to explore the consequences of that specific policy, whereas other studies or a reviews of existing studies (such as the present meta-analysis) are of more limited use in such contexts. However, context-specific studies can still be useful outside their intended use, if the influence of context-dependent factors are carefully analysed and considered. Similarly, more general studies can also be of great value, as they can shed light on aspects that are important to consider – in policy making in general as well as in future, more specific studies (dealing with, e.g., specific policies).

- **Choice of environmental impact indicators** is an important aspect to avoid burden-shifting. For example, if the study is to support policy making, it is key that the choice reflects the intended environmental benefits of the considered policy, as well as likely unintended and relevant environmental drawbacks. Relevance should be defined both in terms of product category and geographical context.

  Relatedly, some environmental aspects are less well-covered by LCA than others. Among others, impacts from littering on marine and terrestrial ecosystems, biodiversity impact of land use, or toxic effects of microplastics released to the marine environment are seldom included in LCAs (none of the studies of the meta-analysis covered these issues). This is probably mainly due to a lack of sufficiently robust and established characterisation methods. An LCA study may therefore have to be complemented by some other type of study to provide a sufficiently complete picture of the

7 *Nationwide and compatible return system used for metal cans and recyclable PET bottles for ready-to-drink beverages (https://pantamera.nu/om-oss/returpack-in-english/about-returpack/).*

environmental impact of a product. Moreover, impacts that are included in the LCA may be associated with very different levels of uncertainties – a 10% difference in climate impact results between two compared products can be a significant and meaningful difference, whereas a 10% difference in toxicity impact results is likely not.

- **Generalizability**. It is tempting to generalise based on individual studies. For example, if a plastic bottle produced from a specific resource by a specific manufacturer, going through a specific end-of-life handling, has clear environmental benefits compared to a similarly specific container of another material, one may be inclined to think the plastic bottle is generally preferable to that other container. However, as is evident when comparing the studies analysed in Sections 2.1 with those analysed in Section 2.2, differences between different types of plastic bottles are often larger than differences between plastic bottles and other containers, suggesting that one should be careful in making generalizations based on individual studies. This underscores the importance of designing a study for a specific aim and context, to cover the expected variations in that studied context, and to cross-check the results with those of other similar studies. However, as emphasised above under the bullet point "Aim of the study", context-specific studies can still be of great value outside their intended use and general recommendations are still possible to make based on these studies, if the context-specific aspects are understood and considered – as is done in the present study, where the variations in context and how these influence environmental impact of compared alternatives are at the core of making meaningful recommendations.

## 3.3 IMPORTANT ASPECTS IN POLICY MAKING

This meta-analysis cannot be used as the sole source for environmentally related advice on specific policy making, such as prohibition of specific containers, taxes and fees, or labelling. But the meta-analysis can give recommendations of aspects that policy making should consider. In other words, it can be used as a starting point of, and complementing, studies designed to assess the impact of specific policies. Below is a non-exhaustive list of such aspects, to some extent mirroring the aspects listed in Section 3.2 for consideration in LCAs.

- **Policies must consider functional differences.** Functional differences between solutions for providing beverages to consumers must be considered in policy making. This includes, for example, their capacity to provide different beverages and volumes to different consumers at different times. For instance, although bigger volumes of bottles show lower environmental impact per litre of a beverage, they cannot always substitute bottles with smaller volumes due to the different purposes of use (e.g., use at home vs take-away). Moreover, different container materials are not completely interchangeable due to different practical issues (e.g., reusable steel bottles vs. plastic bottles). Apart from influencing the relative environmental viability of different container materials (see, e.g., the discussion on volume of beverage container in Section 2.3), functionality also influences to what extent two materials are interchangeable, and policy making should thus not have a too one-sided focus on the material without considering functionality.

- **Policies must consider differences in production within a material category.** A main conclusion from the meta-analysis is that there may be larger differences in the environmental impact within a single container material, due to variations in production, than between container materials. For example, for PET bottles, the choice between fossil-based, recycled and bio-based resources (or different types of bio-based resources) makes a considerable difference to their environmental impact, so does the matureness of production technology (see below bullet point). Policy making should therefore not solely focus on the material of the beverage container, but also account for differences in the production of a certain material.

- **Policies must account for differences in technology maturity.** Whether a certain beverage solution is novel or established, small-or large-scale must be considered in policy making, as its current environmental performance may not be representative for its possible future environmental performance.

- **Policies must consider differences in end-of-life practices.** The meta-analysis illuminates large differences in the environmental impact of beverage containers depending on end-of-life practices. Policy makers should therefore account for these differences, both within and between material categories, and ensure that the studies supporting policy making are based on relevant end-of-life assumptions and best practice in terms of end-of-life modelling. For example, policies concerning PET bottles and aluminium cans should distinguish between countries with high recycling rates due to the existance of deposit systems, and countries without deposit systems with lower recycling rates.

- **Policies must account for future changes**, of production technologies, end-of-life practices and other aspects of the product system influencing its environmental impact. As highlighted above, differences in current technology maturity and end-of-life practices must be considered in policy making. The environmental impact of mature technologies will, however, also likely change in the future, for example as a result of process development and changing energy systems. Likewise, end-of-life practices may change due to, for example, technological advancements and various waste management policy levers. Policy making must therefore rely on future scenario assessments, as a complement to studies on current (and past) product systems.

- **Policies must be geographically adapted.** The meta-analysis provides several examples of results that depend on geographical context. For example, the type of feedstock likely used for bio-based plastics, whether tap water is a direct source of safe drinking water or must be boiled prior to consumption, or to what extent landfilling, incineration or recycling can be expected to be employed at end-of-life. Because these aspects are of outmost important for the environmental viability of different means of providing beverages to consumers, policy making needs to account for how these aspects depend on geography and adapt policies accordingly.

- **Policies must recognise and manage trade-offs and risks of burden-shifting between environmental impacts**. The meta-analysis provides several examples of trade-offs between environmental impact categories, i.e., that a product is preferable in some impact categories but not in others. Policy making must thus consider all potentially relevant impact categories, to avoid the risk of burden-shifting (i.e. one environmental issue is mitigated at the expense of another) between them . Potentially this calls for the combination of policies that jointly are capable of addressing or balancing several relevant environmental issues. Relevance should be defined both in terms of product category and geographical context.

- **Policies must be based on several sources for information on environmental impact.** LCA is an excellent tool for providing scientifically based guidance related to many environmental issues, but the characterisation of some environmental impacts are better than others and some relevant impact categories may not be covered at all due to a lack of methods or data. For example, impacts from littering of marine and terrestrial ecosystems, or toxic effects of microplastics released to the marine environment, are seldom included in LCAs of plastic bottles and their alternatives. Also some resourse constraints, which are highly dependendent on the scale of production – such as availability of agricultural land – are seldom incuded in such LCA. This may be particularly important when comparing bottles made of recycled and bio-based resources, or bottles of different bio-based content (e.g., forestry residues vs. agricultural crops). Therefore, in contexts related to plastic bottles and their alternatives, policy makers should complement the result of LCA studies with additional sources of environmental impact information.

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