Material choices for environment-friendly packaging design

Analysis of existing Life Cycle Assessment (LCA) studies

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Global Project
“Support of the Export Initiative for Green Technologies” (BMU)
Köthener Str. 2
10963 Berlin / Germany
T +49 30 338 424 646
E markus.luecke@giz.de

Collaborative Action for Single-Use Plastic Prevention
in Southeast Asia (CAP-SEA)
193/63 Lake Rajada Office Complex, 16th Fl.
New Ratchadapisek Road, Klongtoey
Bangkok 10110 / Thailand
T +66 65 2400266
E christoffer.brick@giz.de

More information
https://greentechknowledgehub.de/
https://www.giz.de/en/worldwide/78869.html
www.exportinitiative-umweltschutz.de

Authors:
Kevin Stuber-Rousselle
Siddharth Prakash
Clara Löw

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kippconcept gmbh, Bonn

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In cooperation with Öko-Institut e.V.

Contact
info@oeko.de
www.oeko.de

Head Office Freiburg
P. O. Box 17 71
79017 Freiburg / Germany

Street address
Merzhauser Straße 173
79100 Freiburg / Germany
Phone +49 761 45295-0

Office Berlin
Borkumstraße 2
13189 Berlin / Germany
Phone +49 30 405085-0

Office Darmstadt
Rheinstraße 95
64295 Darmstadt / Germany
Phone +49 6151 8191-0

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List of abbreviations

EPS	expanded polystyrene
EVOH	ethylene vinyl alcohol copolymer
GWP	global warming potential
HDPE	high-density polyethylene
HI-PS	high impact polystyrene
LDPE	low-density polyethylene
MP	molded pulp
NWPP	non-woven polypropylene
PA	polyamide
PE	polyethylene
PET	polyethylene terephthalate
PHA	polyhydroxyalkanoate
PLA	polylactic acid
PP	polypropylene
PS	polystyrene
PVdC	polyvinylidene dichloride
rPET	recycled polyethylene terephthalate
SUPB	Single use Plastic bags
TPA	terephthalic acid
TPS	thermoplastic starch
XPS	extruded polystyrene

Executive Summary

There is a growing agreement on negative consequences of increasing single-use plastic and packaging waste to human health, marine and terrestrial ecosystems, climate change and biodiversity. However, implementation of measures to tackle the problem vary considerably. The prevalent inconsistency in the measures to address the problem of single-use plastics and packaging waste is partly due to a lack of knowledge on environmental impacts and potentials of material choices for sustainable packaging designs and single-use plastic alternatives. Life-Cycle Assessment (LCA) methodology offers a comprehensive analysis of the environmental impact of packaging materials, highlighting areas of urgent intervention, and showing potential conflict of interest between different environmental goals. This report is based on a literature review of several LCA studies conducted to analyze the environmental impact of different packaging materials and alternatives. The report focusses on five packaging applications: shopping bags, beverage containers, beverage cups, take-away food packaging and meat packaging.

The analysis conducted in this report leads to following conclusions and consideration for policy development to tackle the problem of single-use plastics and packaging waste in Southeast Asia:

- **Substituting single-use products with other single-use products made from a different material is not an environmental-friendly option**: No single-use product is better than the other in all environmental impact categories. There is just a burden shifting. Thus, although one single-use product may look environmentally preferable than another in a one-to-one comparison, all single-use products have a high burden on resource consumption.

- **Reusable products have a lower environmental impact than single-use products**: Increasing the reuse rate of packaging products has the highest potential for reducing environmental impacts. However, if reuse rates of durable and reusable packaging are low, they do not perform better than the single-use products. Therefore, high reuse rates need to be ensured and collection losses in the reverse logistics of reusable packaging minimized.

- **Environmental burden of additional logistics, transportation and washing cycles for reusable packaging products does not reverse their environmental superiority over single-use products**: Switching to a reusable system has a greater impact on the environmental performance of a reusable packaging than the distance it must be transported to the washing station, and corresponding washing processes using dishwashers. With increasing energy efficiency of dishwashers and increasing share of renewables in the electricity mix, the environmental footprint of a reusable container would shrink even further.

- **Considering the challenges and technical limitations of recycling, it is more important to promote reuse than recycling**: Increasing the reuse rate of packaging has a much higher environmental impact reduction potential than recycling. If reusable packaging products are made from post-consumer recycled material, the environmental impacts are even lower. It is known that collection and recycling rates are relatively low in many countries. Technically recyclability of a material does not mean that it is really recycled in practice.

- **Lack of adequate consideration of hazardous substances, microplastic generation, littering, biodiversity loss and impacts of land-use changes in LCA studies undermines the environmental benefits of reusable packaging**: Reusable products lead to a reduction in the resource consumption. Hence, they cause a lower demand for land-use and extractive activities, thus avoiding land-use conflicts and monoculture plantations that trigger biodiversity losses. The higher weight of the reusable and durable packaging makes it less susceptible to littering than light-weight single-use plastic products. In combination with hazardous substances and microplastic generation, single-use plastic products cause a severe threat to human health, marine & terrestrial environment, and biodiversity.

- **Single-use packaging products made from bio-based plastic offer no advantages over other disposable plastic packaging products:** There is only an environmental burden shifting when fossil-based plastic packaging is replaced by bio-based plastic packaging. While conventional fossil-based plastics have a higher climate impact, bio-based plastics are associated with a higher acidification and eutrophication potential as well as land requirement. Thus, they cause competition for land with food production and also lead to a loss of forest areas, thus threatening biodiversity.

- **Advantages of biodegradable packaging are highly overrated and strongly dependent on the context:** In ambient environment, e.g. home composter, marine water etc., the time required for decomposition is very long. Thus, biodegradable packaging does not solve the problem of littering. In industrial composting plants, biodegradable packaging requires more time to decompose than other organic waste, resulting in management problems for composting plants. Biodegradable plastics also cause sorting problems in the recycling process of fossil-based plastics, leading to quality degradation of the recycled material.

- **End-of-life management in a specific context has a significant influence on the environmental performance of a packaging material:** There is no one-size-fits-all solution for the most appropriate waste management option for all packaging materials. If a country's waste management is mainly landfill, and the reuse rate of reusable packaging is low, recycled plastic packaging may be a better option for the climate. In countries where waste management is dominated by incineration – with or without energy recovery – cotton, paper and starch-based plastics may be better options for the climate. Overall, it can be concluded that recycling has an environmental advantage over landfilling. However, after looking at the complex material-specific choices that need to be considered for selecting best possible waste management option, switching to a reusable system would not only be more practicable, but would also result in an even greater environmental benefit.

- **Environmental impact of a packaging is dependent on several factors, such as weight, size, use of mono-materials, recyclability, energy-mix of production processes and waste treatment option:** These factors need to be analyzed on a case-by-case basis in order to evaluate the environmental performance of a packaging types and alternatives. From an ecological point of view, there is a clear preference for recyclable packaging options made from mono-materials. Trade-offs between recyclability and immediate climate benefits due to weight reduction of a packaging need to be considered. In countries with suboptimal waste incineration plants, complex, non-recyclable packaging with potential low climate impact, could also lead to harmful emissions. In such cases, using a heavier, but better recyclable packaging may be a better alternative.

- **Food packaging should be given a special attention in the debate on sustainable packaging solutions:** Preventing food waste through packaging by extending shelf life has a greater environmental impact than reducing the environmental impact of packaging. Putting a broader and systemic perspective, it will be important to question the meaningfulness of transporting fresh food products over long distances and storing them for extremely long shelf life. Instead, approaches for developing seasonal and regional food value chains for fresh, largely vegetable-based products with small distances, less storage requirements and immediate consumption will be important. Several LCA studies have clearly shown the environmental benefit of seasonal and regional food chains with a large vegetable share.

1 Introduction

The debate on environmental impacts of increasing single-use plastic and packaging waste has been going on for few years now. It will not be an overstatement to declare that a global societal consensus on the urgency to reduce such waste related problems is emerging. This can be observed in the plethora of international agreements, national and regional policies, and numerous private sector initiatives worldwide. While there is a growing agreement on negative consequences of increasing single-use plastic and packaging waste to human health, marine and terrestrial ecosystems, climate change and biodiversity, implementation as well as understanding on the impact of measures to tackle the problem vary considerably. The prevalent inconsistency in the measures to address the problem of single-use plastics and packaging waste is partly due to a lack of knowledge on environmental impacts and potentials of material choices for sustainable packaging designs and single-use plastic alternatives.

Life-Cycle Assessment (LCA) methodology offers a comprehensive analysis of the environmental impact of packaging materials, highlighting areas of urgent intervention, and showing potential conflict of interest between different environmental goals. At the same time, LCA studies do not always provide a complete picture, and need to be supplemented by additional information that are more context-specific and address aspects that are not dealt with by LCA studies.

This report is based on a literature review of several LCA studies conducted to analyze the environmental impact of different packaging materials and alternatives. The report focusses on five packaging applications: shopping bags, beverage containers, beverage cups, take-away food packaging and meat packaging. It is important to emphasize that this report is not based on own LCA modelling, but rather synthesizes the information and results generated in a number of LCA studies. The analyzed LCA studies are not comparable with each other. They are conducted by different authors in different regions using different data sets and assumptions. Nevertheless, this report, while not undermining the inherent differences in the LCA studies, has drawn some overarching conclusions and recommendations in order to guide a more informed decision-making towards sustainable packaging solutions.

This report has been prepared by the Öko-Institut, Germany. The target audience of this report are the political decision-makers and companies in Thailand, Malaysia, and Indonesia. Currently, the target audience in the abovementioned countries are supported by the GIZ project module CAP SEA (Collaborative Action for Single-Use Plastic Prevention in Southeast Asia). The aim of the CAP SEA project is to support in reducing plastic waste and promoting reusable packaging systems in Thailand, Malaysia, and Indonesia by focussing on upstream approaches and embedding those in broader circular economy strategy advice to the government.

CAP SEA is funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and is part of the global project to support the "Export Initiative for Green Technologies". GIZ is the main implementer while the implementation period runs from August 2019 to March 2023.

2 Packaging types

2.1 Shopping bags

Shopping bags are bags that are used to transport goods while shopping. The most commonly used bag worldwide is the **single-use plastic bag (SUPB)**, also known as disposal bag, which is used for about 15 minutes on average and then thrown away. An estimated 500 billion shopping bags are used worldwide each year (Plastic Oceans 2021). However, there are alternatives to single-use plastic bags. This chapter is about the environmental footprint of the disposable shopping bag and its alternatives.

2.1.1 Most common materials

Disposable or **single-use plastic bags (SUPB)** are commonly made from **low-density polyethylene (LDPE)** or **high-density polyethylene (HDPE)**. **Paper** bags are also usually single-use carrier bags.

Reusable plastic bags are carrier bags produced for multiple uses and are commonly made from **polypropylene (PP)** or **polyethylene terephthalate (PET)**. **Cotton** bags produced out of woven cotton are also used as alternative to reusable plastic carrier bags.

Bio-based plastic bags are carrier bags that are usually produced for single use only. However, reusable bio-based bags are also available on the market. Bio-based plastic bags are commonly made from **bio-based raw material** such as **polylactic acid (PLA), organic waste material, crops such as sugarcane, corn,** or sometimes also **wood.** "Biobased" does not always mean that 100 % of the raw materials are renewable. Biobased plastics can also be used in a composite also containing petroleum-based plastics. Bio-PET, for example, consists of 30 percent sugarcane and 70 percent fossil resources (DUH 2018a).

Biodegradable plastic bags are carrier bags that are also generally produced for single use. They can be produced from either bio-based or fossil-based raw materials. Typical bio-based raw materials for producing biodegradable plastic bags are starch, cellulose, carbohydrates, e.g. obtained from potato, cassava, etc. and PLA. They are designed to biodegrade under specific conditions[1], releasing CO_2 and methane emissions.

Oxo-degradable plastic bags are carrier bags produced for single use only. They are made from conventional plastics such as PE and from additives[2]. These plastic bags are designed to break down into their fragments as microplastics after use.

2.1.2 Environment performance

The weight of the shopping bags has an impact on its environmental performance. An SUPB weighs about 6 g in China, India, Singapore and the USA, but 18-20 g in Finland, Spain, and the UK (UNEP 2020a). If both types of bags meet the same functional unit, the bags from Finland, Spain and the UK have an environmental footprint three times higher than the bags from China, India, Singapore, and the USA. However, the 18-20 g bag is probably larger than the 6 g bag and can therefore carry more material. A heavier weight, however, could also mean that the bag is sturdier and can be used several times. However, the 18-20 g bag must replace three 6 g bags so that the two SUPBs can be compared in terms of their environmental performance. The distance over which a bag has to be transported before use does not seem to have a significant impact on its environmental performance (Khoo et al. 2010; Edwards und Fry 2011).

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[1] Most biodegrading plastics are designed to decay at conditions of an industrial composting plant.

[2] Metal-ion such as Cobalt, manganese, iron.

The study of Civancik-Uslu et al. (2019) compare three single-use bags made from HDPE, paper and biodegradable plastics with two reusable bags made from LDPE and PP. The study also includes the impact category littering potential. The littering potential considers among other things the weight of a bag, the degradation rate of the bag and the price of a bag (it is assumed that cheaper bags are more likely to be thrown away). The authors conclude that:

- the single-use HDPE bag performs almost 30 times worse than the reusable LDPE bag in terms of littering potential,
- the other three bags perform several times better than the LDPE bag in terms of littering potential,
- the single-use HDPE bag performs equally or better than the other bags in terms of photochemical ozone creation, water use, acidification, and eutrophication,
- the reusable LDPE bag has the lowest carbon footprint, followed by the single-use HDPE bag,
- the paper bag and the reusable PP bag have the highest carbon footprint but perform best in terms of the littering potential,
- the paper bag, reusable PP bag and biodegradable bag perform worst in terms of eutrophication,
- the biodegradable bag has the highest water consumption.

Thus, there is no bag that is better than the others in all impact categories. A lighter material may result in lower climate impacts, as is the case of the HDPE single-use bag and the LDPE reusable bag, but it may also result in greater littering potential. The lighter material is more likely to be picked up by the wind.

The study of the European Commission (2019) compares a single-use LDPE bag, a biodegradable bag and a bio-based LDPE bag. The biodegradable bag is made from starch and co-polyesters. The bio-based LDPE bag is produced in Brazil from sugarcane, while the other bags are produced in Europe. As an overall conclusion, no bag material in this study is clearly preferable. The bio-based LDPE bag has the lowest carbon footprint and fossil fuel consumption compared to the other two bags. The low results in these two impact categories are accompanied by a trade-off in the other impact categories. The bio-based LDPE bag performs the worst in the impact categories of acidification, eutrophication, particulate matter, and photochemical ozone formation. The disposable LDPE bag performs slightly better in environmental terms than the biodegradable bag.

According to the European Commission (2019), biodegradable plastics affect the Global Warming Potential (GWP) in landfills much more than LDPE bags due to the release of methane in the composting process. LDPE bags are inert and do not release emissions in landfills. Comparing the credits from the composting process of starch-based bags with the credits for recycling LDPE bags, the credits from the recycling process are much higher than the credits from composting. The climate benefit of recycling LDPE is much greater than the benefit of composting biodegradable plastic bags. This is due to the fact that recycling LDPE leads to a replacement of new fossil material, while compost only replaces fertilizer (European Commission 2019).

If a country's waste management is mainly landfill, and the reuse rate of reusable bags is low, recycled plastic bags may be a better option for the climate. In countries where waste management is dominated by incineration – with or without energy recovery – cotton, paper and starch-based plastics may be better options for the climate. However, the latter strongly depends on the weight of the bags, the actual reuse rate of these bags and the production process of the paper (UNEP 2020a).

The study of Kimmel (2014) compared four single-use bags, a conventional HDPE bag, a partially recycled HDPE bag, a partially recycled paper bag and a 100 % recycled paper bag, with two reusable bags, one made of LDPE and one made of non-woven polypropylene (NWPP). The partially recycled HDPE bag is made of 30 % recycled and 70 % virgin material. The partially recycled paper bag is made from 40 % recycled material and 60 % kraft paper. Main results are:

- The disposable bag made of partially recycled paper performs worst in all environmental impact categories.
- The paper bag made from 100 % recycled paper performs better than the paper bag made from partially recycled paper in all environmental impact categories, except for fossil fuel consumption and marine eutrophication, where both perform similarly.
- However, the 100 % recycled paper bag performed worse than the SUPBs in all environmental impact categories except acidification and freshwater as well as marine toxicity.
- If the paper bag is reused 3.7 times, it is environmentally better than the SUPBs.
- The partially recycled HDPE bag performed 0-30 % better than the virgin HDPE bag in all environmental impact categories.
- The reusable bags perform best in terms of environmental impact if they are used often enough. If they are used only once, they perform worst.
- The reusable LDPE bag performed better than the reusable PP bag.
- The reusable LDPE bag needs to be reused about 6-9 times to be better than the partially recycled HDPE bag and the reusable PP bag needs to be used 13-20 times to be better than the disposable options.

Muthu et al. (2011) compare an SUPB made of PE, a paper bag, a NWPP bag and a cotton bag. They examined the impact of these bags on the climate change category. It was assumed that the reusable PP bag replaced 100 SUPBs and the cotton bag replaced 50 SUPBs. The geographical region of the study was Hong Kong, China and India. In their study, the paper bag performed worst. According to the authors, the paper bag consumes "a tremendous amount of energy from fossil fuels, electricity, chemicals, etc." The SUBP and reusable cotton bag have comparable carbon footprints, which are both lower than the paper bag. The reusable PP bag performs best. The authors conclude that recycling and reuse reduce the carbon footprint of a shopping bag.

In their study, Khoo et al. (2010) compare a single-use bio-based bag made from corn with a disposable bag made from fossil PP plastic. The study was conducted in Singapore. The bio-based bags are manufactured in the USA. The authors further establish that the bio-based bag has a higher global warming potential (GWP), acidification and ozone depletion than the fossil PP bag which is mainly attributable to the high energy consumption during the production phase of the bio-based plastic. In particular, the conversion of glucose into polymers requires high amounts of energy. The authors conclude that shipping from overseas does not have a significant impact on the results.

2.1.3 Recyclability

In general, many shopping bag materials such as PP, HDPE, LDPE or paper are recyclable[3]. In practice, however, these bags are often not recycled. This is not for technical reasons, but because the bags do not enter the recycling waste stream. In some life cycle assessments, this is acknowledged with low or no recycling values. This is also attributable to the fact that SUPBs are often reused as trash bags after their first use as shopping bags (Muthu et al. 2011). Therefore, they end up in the residual waste stream instead of the recycling waste stream.

An analysis of different LCA studies that were carried out in different world regions show a variety of assumptions when it comes to the recyclability of the shopping bags:

- Civancik-Uslu et al. (2019) estimate that half of the paper bags and a smaller proportion (10 %) of HDPE, LDPE, and PP bags are recycled after use. The scope of the study is Spain and Denmark,

- The study of Kimmel (2014) assumes similar recycling rates for the US,

- In contrast, a study by the European Commission (2019) assumes that about 30 % of plastic bags are recycled at the end of their life cycle,

Muthu et al. (2011) use data from a consumer survey by Li Yi et al. (2010) in their LCA, in which the behaviour of people from China, Hong Kong and India was analyzed. According to Muthu et al. (2011) the recycling of shopping bags is highly dependent on consumer behaviour. They assume following recycling rates:

- China
  - 21 % for plastic bags
  - 31 % for paper bags
  - 22 % for non-woven bags

- Hong Kong
  - 22 % for plastic bags
  - 25 % for paper bags
  - 25 % for non-woven bags

- India
  - 18 % for plastic bags
  - 25 % for paper bags
  - 21 % for non-woven bags

As regards biodegradable and bio-based plastics, in addition to the risk of these plastics entering the wrong waste stream, there is also a technical problem with recycling. If they enter the recycling stream, they can cause sorting problems in the recycling process of fossil-based plastics (UNEP 2020a). Most recyclers are not able to differentiate between bio-based and fossil-based plastics, which leads to quality degradation of the recycled material.

On the other hand, using recycled material in manufacturing can also significantly reduce the environmental footprint of a shopping bag. If a plastic bag has a recycled content of 30 %, it is 0-30 % better than a bag made from 100 % virgin material, depending on the impact category (Kimmel 2014). Using recycled material also reduces the environmental footprint of paper. A 100 % recycled paper bag performs better than a kraft paper bag in each impact category. However, the paper bag made from 100 % recycled paper material still has a higher environmental footprint than a SUPB made from virgin plastic, except for acidification and freshwater as well as marine toxicity.

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[3] Recyclable or recycled refers to end-of-life treatment, while the use of recycled material means that recycled material is used in production instead of virgin material.

2.1.4 Reusability

The reuse rate has a major impact on the environmental performance of a shopping bag. A bag's higher reuse rate has a bigger influence on its carbon footprint than its recycling rate (Muthu et al. 2011). Reusable bags could be environmentally superior to SUPBs if they were reused many times. How often a cotton bag needs to be reused strongly depends on the study investigated. For example, according to (UNEP 2020a), a cotton bag needs to be used 50-150 times to have less climate change impact than a SUPB, while the Environmental Action Germany (DUH) estimates that a cotton bag needs to be reused 25-32 times to be environmentally comparable to a SUBP (DUH 2021).

Furthermore, the popularity of reusable shopping bags out of PP, PE and PET is increasing. They are cost effective and in some cases only need to be reused three times to have less impact on climate change than SUPB (DUH 2021). A thick and durable PP bag is estimated to need to be used 10-20 times and a thinner but still reusable PE bag 5-10 times to have the same climate change impact as a SUPB. This requires not only that the bags have a long shelf life, but also that consumers reuse each bag multiple times (UNEP 2020a). More and more of the reusable plastic bags are made from recycled material, which makes them even more environmentally friendly. In Germany, for example, up to 90 % of reusable PET bags are made of recycled plastic bottles (DUH 2021).

The study by Muthu et al. (2011) uses data from a consumer survey (Li Yi et al. 2010) in which the reuse rate of durable PP bags is 78 % in China, 69 % in Hong Kong and 55 % in India. The reuse rate of cotton bags (73-80 %) is higher than that of single-use plastic bags which are reused between 42-55 % (Muthu et al. 2011). It is assumed that the disposable plastic bags are partially reused as garbage bags. Therefore, the term "single-use" is not quite accurate, but the plastic bags are used only once for their original purpose of use as a shopping bag.

The reuse rates from the different countries indicate that a durable PP bag is used only 2-5 times depending on the country, while a cotton bag is used 4-5 times. These reuse rates are far below the break-even point that these various bags must reach to be ecologically comparable to single-use plastic bags. These consumer survey reuse rates differ from the reuse rates assumed in other LCA studies' baseline scenario. For example, Muthu et al. (2011) assume that a cotton bag replaces 50-150 disposable bags in Finland. In their baseline scenario, Muthu et al. (2011) also assume that a cotton bag replaces 50 disposable bags (this is in conflict with the 4-5 times the cotton bag is reused in the consumer survey). Kimmel (2014) estimates that durable PP bags are reused 14.6 times in the USA.

It looks as if the reuse rate assumed in many studies does not correspond to the actual reuse rate. There are also large differences in the reuse rate between countries and continents. Many LCA studies focus on Europe or the USA (Kimmel 2014; Muthu et al. 2011), while reuse rates in Asia or Africa are assumed to be lower. A reusable bag can be superior to the single-use options if its reuse rate is high enough.

2.1.5 Summary

Reusable shopping bags have a lower environmental impact than single-use bags. However, the reuse rate of reusable bags is a decisive factor. Higher the reuse rate, lower the environmental impact. If reuse rates of durable and reusable bags are low, they do not perform better than the SUPBs. Reusable bags tend to have a greater environmental footprint in the production phase than disposable bags because of a more durable material used. Once the reusable bag is used often enough, the higher energy consumption in the production phase is compensated. If the reusable bag is reused beyond the break-even point, its environmental footprint is reduced even further. The number of times a reusable bag needs to be reused to be ecologically comparable to a SUPB depends on the material.

There are also reusable shopping bags made of plastics such as PP, PE, or PET, which are becoming increasingly popular. This is also due to their low cost and good environmental performance. They need to be reused less often than cotton bags, making them more environmentally friendly than a SUPB. Environmental impact of shopping bags can be reduced even further if reusable bags are made from recycled material.

Due to their higher weight, reusable plastic bags have a smaller littering potential than SUPBs. However, they still give rise to the same problems as those related to SUPBs if they end up in nature, causing microplastic pollution and having physical impacts on animals. On the other hand, due to their light weight, single-use plastic bags have a high littering potential. They are easily picked up by the wind and end up as litter instead of in their intended waste management. Unfortunately, littering potential is not considered in most life cycle assessments.

When it comes to the material choice of shopping bags, there is no single-use bag that is better than the others in all environmental impact categories. The material type and weight of a shopping bag are important characteristics for determining the environmental impact of shopping bags. A bag made of the same material, but with twice the weight doubles its environmental impact unless it is reused more often or used to transport more goods.

Single-use bags made from biodegradable or biobased plastic offer no advantages over other disposable plastic bags. They are just as short-lived and generate the same amount of waste. Furthermore, they cause sorting problems in the recycling process of fossil-based plastics. Their potentially lower carbon footprint is being nullified by higher emissions in other impact categories such as acidification, eutrophication, particulate matter and photochemical ozone formation. . Rather, the designation “biodegradable” belies the problems associated with this group of plastics, such as: improper disposal in the organic waste garbage can, careless littering, and careless use of disposable products (Umweltbundesamt 2021).

2.2 Beverage containers

A beverage container is a vessel for transporting or drinking beverages. A large portion of beverage containers belongs to the category of single-use packaging. For instance, 70 % of soft drinks in the UK are packaged in single-use PET bottles. The remainder are cans, multilayer beverage cartons, or glass (BSDA 2021). However, there are alternatives to single-use plastic bottles. This chapter is about the environmental footprint of the single-use beverage container and its alternatives.

2.2.1 Most common materials

Single-use **plastic bottles** are commonly made from **PET, recycled PET (rPET), or HDPE**. Single-use plastic bottles made from **bio-based raw material** are also available in the market.

Glass bottles can be single-use or reusable beverage containers, while **aluminum cans** are commonly single-use beverage containers.

Multilayer beverage carton packaging is usually a single-use beverage container. It is commonly produced from multiple layers of carton, plastics, and aluminum.

Reusable beverage bottles are commonly produced from variants of materials such as **steel, aluminum, PP,** or **glass.**

Non-container consumption means that no material is used for the transport of the beverage or for the drinking process. The beverage, for example water, is drunk directly from the tap.

2.2.2 Environment performance

The study by Benavides et al. (2018) compares three types of PET bottles (virgin, recycled and bio-based PET). The recycled PET bottle modelled in the study is made of 35 % recycled material and 65 % bio-based or virgin material. According to their study, the 100 % bio-based bottle has a better carbon footprint than the 100 % fossil-based one. It's carbon footprint is lower than that of a mix of recycled PET and fossil PET as well as a mix of recycled PET and bio-based PET. Furthermore, Benavides et al. (2018) compare two different methods for producing terephthalic acid (TPA) from bio-based plastic. They found that the production on the basis of an isobutanol intermediate performed 88 % better in the carbon balance than that of the fossil-based PET bottle, while production from direct fermentation of sugars performed 22 % better than that of the fossil-based bottle. The authors suggest that:

- higher use of bio-based PET instead of fossil-based PET leads to a reduction in GWP and fossil fuel consumption.
- A combination of bio-based PET and recycled material performs 35 % to 73 % better in terms of the GWP than a fossil-based PET bottle.
- The combination of bio-based PET made from an isobutanol intermediate and recycled material has the lowest fossil fuel consumption: it is 59 % less than that of a fossil-based PET bottle.
- The second-best option in terms of fossil fuel consumption is bio-based PET, which is made from an isobutanol intermediate and consumes 50 % less fossil fuel than a fossil-based PET bottle.
- The authors do not compare a bottle made from 100 % recycled material, but their results indicated that it would have a smaller carbon footprint than the bio-based bottle obtained through a direct fermentation of sugars, but not smaller than the bio-based PET bottle made out of isobutanol intermediate.

In the study by Chen et al. (2016), the bio-based PET bottle, in terms of GWP, performs better than the fossil-based PET bottle when avoided impacts are included and worse when they are not included. Avoided impacts are environmental impacts that are avoided through the use of the material and are therefore accounted for as credits. For example, the authors assign credits for the wood bio-based PET bottle for avoiding the burning of brushwood piles due to the harvesting of non-tradable crop residues. Burning brushwood piles is a common practice in the Pacific Northwest to reduce wildfire risk. However, burning brushwood piles is not common practice in every region. Whether these credits can be accounted for or not depends on the geographic scope of the study. Avoided impacts should be interpreted with caution if they are sensitive to the results and especially if they are used unilaterally (for only one product) in a comprehensive LCA. The authors compare different bio-based PET bottles with each other:

- The best-performing bio-based PET bottle contains TPA made from wood.
- PLA which is made from agricultural products such as corn has environmental disadvantages due to the related additional energy consumption at farms and/or the production of the chemicals used.
- The fossil-based PET bottle performs better than the bio-based PET bottle for the environmental impacts of acidification, terrestrial eutrophication, ecotoxicity, smog and ozone depletion, with and without avoided impacts. Hence, the use of bio-based plastics can lead to a trade-off: potentially lower global warming potential, but higher environmental impacts in other categories.

Another study found that bio-based PLA (from cassava) has an advantage over fossil-based PET in terms of GWP, fossil energy use, and human toxicity, but a disadvantage in acidification and eutrophication (Papong et al. 2014). Schlecht et al. (2019) arrive at a similar trade-off, where the switching from a fossil-based PE to a bio-based PE in a multilayer beverage carton packaging system resulted in lower GWP, but higher impacts in terms of other environmental impacts.

The study by Papong et al. (2014) concludes that the environmental performance of PLA is strongly influenced by waste treatment. In a waste treatment scenario for landfill, PET bottles perform 30 to 100 % better than PLA bottles in terms of GWP. This is related to the fact that PET bottles are inert in landfills and PLA bottles release methane in landfills. If this methane is not captured, it will lead to high climatic impacts. The best waste treatment scenario for PLA bottles is incineration with energy recovery, while for PET bottles it is recycling (Papong et al. 2014).

Another alternative to fossil-based single-use bottles, apart from bio-based plastics, are multilayer beverage carton packaging systems. According to Markwardt et al. (2017) and Schlecht et al. (2019), multilayer beverage carton packaging systems, in terms of environmental friendliness, should be considered preferrable to PET bottles, HDPE bottles, glass bottles, PP containers with aluminum closures and stand-up pouches in most beverage segments (except water). The fossil-based PET bottle only performed better for the impact category of aquatic eutrophication. Using bio-based plastic as cap instead of fossil-based plastic for the multilayer beverage carton packaging system results in lower GWP but increases the environmental burden in other impact categories (Markwardt et al. 2017; Schlecht et al. 2019).

The study by Amienyo et al. (2013) compared single-use glass bottles, aluminum cans and PET bottles. It concludes that:

- 2-liter PET bottles have an advantage over the other two materials in most environmental categories.
- Aluminum cans perform best in the environmental categories of eutrophication, terrestrial ecotoxicity and ozone depletion.
- Glass bottles perform worst in all environmental categories except eutrophication and freshwater aquatic ecotoxicity.
- A glass bottle needs to be reused three times to be environmentally comparable to a 0.5-liter PET bottle and an aluminum can.
- In addition, the size of the container plays an important role: 2-liter PET bottles perform better in ecological terms than 0.5-liter PET bottles.

To achieve the same functional unit of a given beverage volume, a larger bottle results in a lower bottle-material-beverage ratio and thus in a better environmental performance. Markwardt et al. (2017) reached a similar conclusion. In their study, the functional unit was 1000 l of beverage and they conclude, that the larger the volume of a bottle, the lower the environmental impact.

There have also been comparisons of tap water and single-use plastic bottled water. Tap water outperforms single-use plastic bottles in all categories of environmental impact (Garcia-Suarez et al. 2019; Dettore 2009), since for tap water no production, packaging, and end-of-life phase is required.

2.2.3 Recyclability

A major benefit of recycling is that it leads to a reduction in the use of virgin materials, often reducing environmental impact. Recycling is especially important for non-renewable resources such as fossil-based plastic bottles. Therefore, recycling is believed to be the best waste treatment for fossil-based PET bottles (Papong et al. 2014). In the study by Amienyo et al. (2013), the authors conclude that increasing the recycling of PET bottles from 24 % (assumed average status in the UK in 2009) to 60 % would reduce the climate impact of a PET bottle by 50 %. Benavides et al. (2018) come to a similar conclusion: Using recycled material instead of new material leads to a reduction in environmental impact.

The use of recycled content varies strongly among the materials and often differs strongly from the recycling rate of a country. For example, there are PET bottles made from 100 % recycled material on the market even though there is no country with a 100 % recycling rate. In their study, Amienyo et al. (2013) assumed that the body of an aluminum can consists of 48 % recycled material, and a glass bottle 35 % recycled content. The PET bottle was assumed to be produced from 100 % virgin material. As the use of recycled material in PET bottles has increased in the EU since 2013, also against the background of the EU single-use plastic directive that requires a minimum of 25 % recycled plastic for beverage bottles form PET by 2025, it is expected that environmental benefit of single-use PET bottles compared to those of single-use glass bottles and aluminum cans will increase even further in few environmental categories. Furthermore, it needs to be assessed if aluminum cans and glass bottles still perform better that a PET bottle in other environment categories, such as eutrophication.

Recycling rates vary by region and country. In Malaysia, according to the (World Bank 2021a), the collected for recycling rate for PET packaging (including PET bottles, sheets and films) lies between 28 % to 45 % and the recycling rate for PET beverage bottles is estimated to be 55 % in 2019. However, none of the PET bottles collected is recycled into food grade materials due to the legal uncertainty with respect to obtaining halal certification for using rPET in food grade applications (World Bank 2021a). In Thailand, the collected for recycling rate for PET packaging lies between 31 % to 62 % in 2019, while only 3 % of the PET packaging is recycled as food-grade rPET. The ban in the use of rPET in food grade applications in Thailand is the reason for low rates of rPET production (World Bank 2021b). In Indonesia, the collected for recycling rate of PET bottles in Indonesia is 22 % (GA Circular 2019). The collection for recycling rate of PET bottles is lower than the international average, which was assumed to be 54 % in 2020 (GA Circular 2019).

2.2.4 Reusability

Single-use glass bottles perform worse than single-use plastic bottles in all environmental impact categories except eutrophication, where they comparable or better (Amienyo et al. 2013; Schlecht et al. 2019). A glass bottle must be used three times to be ecologically comparable to single-use plastic bottles (Amienyo et al. 2013). The same is true for reusable aluminum bottles, which must also be used three times to be ecologically comparable to single-use plastic bottles (PathWater 2019). Detzel et al. (2016) conclude that in Germany a reusable glass bottle performs better ecologically than a single-use plastic bottle due to sufficient reuse rates. When the reusable option is used beyond the break-even point, its environmental performance is always better than that of the single-use plastic option.

A glass bottle that is reused in a deposit return scheme (DRS) has a significantly lower environmental footprint (150 kg CO_2 -equivalent/m^3) than a glass bottle that is recycled after single-use (350 kg CO_2 -equivalent/m^3) (DUH 2020). The same holds true for mineral water in a DRS PET bottle (69 kg CO_2 -equivalent/m^3) versus a DRS glass water bottle (84 kg CO_2 -equivalent/m^3) and a single-use PET bottle (139 kg CO_2 -equivalent/m^3) (DUH 2020). This means that a reusable glass bottle should be preferred over a single-use plastic bottle. The savings would be even higher if a reusable PET bottle is used instead of single-use PET bottle.

Krüger et al. (2010) reach a similar result. They compared beer served in reusable glass bottles (with a rate of 25 refills) with disposable PET bottles, disposable aluminum cans, and disposable glass bottles. They conclude that a reusable glass bottle has:

- less than half the GWP of the disposable glass bottle,
- half of the GWP of the aluminum can, and
- 37.5 % less GWP than the disposable PET bottle.

2.2.5 Summary

The use of bio-based PET instead of fossil-based PET can lead to a reduction in GWP and fossil fuel consumption but may increase water consumption and eutrophication. Recycling fossil-based PET can improve their environmental footprint, but bio-based PET may still be preferable in terms of GWP. On the other hand, fossil-based PET bottles are preferable to PLA due to high methane emissions when waste treatment is performed in a landfill.

In addition to the material, the container size also plays an important role. Due to the better ratio between packaging and beverage, a beverage in a larger bottle consumes less material per liter of beverage. If the difference between two materials is not too great, changing the size of the container can change the order of the material performance.

A similar concept to reduce the material per drink ratio is promoting reusable bottles. By reusing a bottle, less material per drink is needed. It is not required to produce a completely new bottle for a new drink. The bottle only must be rinsed between uses. Reusable bottles with enough reuse cycles perform better than single-use options.

A single-use glass bottle is the worst option for beverage containers, but if reused three times, it is environmentally comparable to a single-use aluminum can or a single-use PET bottle with 100 % virgin material. The number of times a bottle is used has a significant impact on its environmental performance. The same is true for aluminum bottles. When used like a single-use bottle, they have a significantly higher environmental impact than single-use plastic bottles. However, when a reusable aluminum bottle is used more than three times, it has a lower climate impact than single-use plastic bottles. Each additional use reduces the environmental footprint. If the reuse rate of a reusable bottle is high enough, reusable bottles are preferable to a single-use variant from an environmental point of view. Reusable options can reduce the amount of waste.

For single-use bottles, recycling is the preferred waste treatment. However, as recycling rates in Malaysia and Indonesia show, not all PET bottles are recycled. Instead, PET bottles end up in landfills or leak into the environment. Therefore, a waste reduction option such as reusable bottles would be preferable.

The best alternative is a non-container consumption such as tap water. However, tap water and disposable bottled water do not have the same functionalities. For example, tap water alone is not portable. To be portable, tap water needs a bottle like a reusable one. In addition, whether tap water is potable varies from region to region.

2.3 Beverage cups

Single-use beverage cups are a widely used packaging system for take-away drinks. However, as easily and quickly as they are used, they are also thrown away and end up as potential marine litter. More than 500 billion single-use cups are consumed worldwide each year and not all of them end up in our waste management system but rather as litter around the world. This chapter is about the environmental footprint of the different materials of single-use cups and their reusable alternatives.

2.3.1 Most common materials

The most common materials for beverage cups are:

Fossil-based single-use plastic beverage cups can be made from a wide span of plastics. The most commonly used materials are **polystyrene (PS), expanded polystyrene (EPS), high impact polystyrene (HI-PS), Polycarbonate, PE, PET and rPET**. Additionally, single-use plastic beverage cups can also be made from **bio-based materials**, such as **PLA, organic waste material** or **crops such as sugarcane and corn**.

Single-use paper cups usually come with a plastic or wax lining. The plastic lining can be based on **fossil** or **bio-based material**. The plastic or wax lining prevents the paper from becoming soggy.

Reusable plastic cups are more durable and made for multiple uses. They also can be made from a wide span of materials. The most common ones are **PP, HDPE,** and **LDPE.**

Non-plastic reusable cups are commonly made using **ceramic** and **glass** for non-take-away purposes, and **stainless-steel** cups or **bamboo** for take-away purposes.

2.3.2 Environment performance

The study by van der Harst und Potting (2013) compared different LCA studies for disposable cups and concludes that no disposable cup material has a consistent environmental benefit compared to the other material options. They compared PLA cups, fossil-based cups such as HI-PS, EPS, PP, PET, and rPET, and paperboard cups with PE, PLA, and wax liners. The GWP differences are due to various factors such as cup weight, production process, allocation options, and waste treatment.

In a later study, van der Harst et al. (2014) conclude that:

- a disposable cup made of PLA and a disposable paper cup with a PLA lining has advantages over a disposable cup made of PS for the impact categories GWP and abiotic depletion.
- However, the PS cup was found to perform better than the two other cups in the impact categories cumulative energy demand, acidification, eutrophication, photochemical oxidation, human toxicity, fresh water and marine aquatic eco-toxicity, terrestrial eco-toxicity, and ozone layer depletion.

The choice of a paper or organic plastic cup instead of a PS cup inevitably leads to a trade-off: lower GWP and abiotic depletion for higher environmental impacts in a large number of other categories.

The environmental performance of the paper cup also depends on the age of these studies. In older studies paper cups perform worse than in more recent studies. UNEP (2021) suggests that most variants of the paper cup would have significantly lower environmental impacts in the production phase if modeled with the latest available datasets. This is due to the lower energy consumption in the more recently modeled data sets for paper production.

Foteinis (2020) compares disposable paper cups, which have PE inserts and end up in landfills or are recycled, with reusable PP cups. In summary:

- paper cups with PE liners that are recycled have an environmental benefit compared to those ending up in landfills.
- The environmental footprint of the paper cup sent to recycling is 40 % less than that of a paper cup sent to landfill. During the landfill process, the paper cups decompose and release CO_2 and methane. These greenhouse gas emissions can be saved by recycling paper. It is obvious that recycling also avoids the production of new material and therefore leads to a lower environmental impact.
- Furthermore, it was found that switching to a reusable PP cup reduces emissions by 69 % compared to the disposable paper cup with landfill waste.
- The recycled paper cup is worse than the reusable PP cup in all environmental impact categories except human health. It is assumed that the cup is reused 500 times and that >90 % of its emissions occur during the washing process.
- It is concluded that recycling has an environmental advantage over landfilling. However, switching to a reusable system results in an even greater environmental benefit.

In another study, it was found that reusable cups made of PP, glass, or bamboo have an 88 % lower GWP than paper cups with PLA linings (Almeida et al. 2018).

CupClub (2018) compare the environmental profile of CupClup – a reusable beverage packaging service in the UK, including the transport to a central washing station, the washing and drying – with disposable PE-lined paper cups, disposable PLA-lined paper cups, disposable EPS cups and reusable ceramic cups. CupClup cups are made of PP, and their waste management is assumed to be 90 % recycling, 5 % landfill, and 5 % incineration. The authors conclude that:

- The CupClup cup has a lower GWP than the disposable paper cup, EPS cup, and ceramic cup. For the CupClup cup, electricity consumption in the washing phase accounts for at least 80 % of all impact categories except water consumption.
- The profitability threshold of the CupClup cup is 72 uses compared to the disposable paper cup and 100 uses for the Styrofoam cup.
- If the disposable paper cup has a recycling rate of 80 %, the CupClup cup must be used 132 times to be environmentally comparable. The expected useful life of a CupClups cup is assumed to be 132 uses.
- A ceramic cup must be used 2000 times to break even with the CupClub.

In addition, the authors in CupClub (2018) performed a sensitivity analysis to examine the impact of backhauling. Increasing the transport distance by a factor of 10 increases the results of most impact categories by less than 0.5 % (except for terrestrial ecotoxicity). Therefore, the distance given in case that a reusable cup must be transported to the washing station does not have a significant impact on environmental performance. Switching to a reusable system has a greater impact on the environmental performance of a beverage cup than the distance it must be transported to the washing station.

Martin et al. (2018) compare hot beverages served in ceramic mugs washed by hand or in a dishwasher to paper cups with PE liners and PS lids. The geographic region of the study is Germany. They investigate the influence of the rinsing method of the reusable cup on the environmental performance of a reusable cup and analyze if hot beverages should be served in reusable ceramic cups or single-use paper cups. Waste disposal is accomplished by using incineration. They conclude that:

- hot beverages should be served in reusable ceramic mugs, and that the rinsing method as well as the water temperature significantly influence the environmental footprint,
- the ceramic mug with or without lid that was washed in the dishwasher has the lowest environmental impact, while the ceramic mug with lid that was washed by hand and with hot water has the highest environmental impact,
- the dishwasher-washed ceramic cup performed better than the hand-washed ceramic cup in all examined 14 impact categories,
- a ceramic mug without a lid, washed by hand without hot water, has a lower environmental impact than that washed by dishwasher. Thus, the environmental impact of hand washing depends heavily on whether the water is hot or not,
- the paper cup falls between the two extremes of the ceramic cup,
- the environmental break-even point for ceramic mugs washed in a dishwasher equivalent to a paper cup is 11 uses without a lid and 13 uses with a lid, and
- the ceramic cup without lid washed by hand and with hot water must be used 89 times and with lid over 750 times to be environmentally comparable to a single-use paper cup.

The study by Woods und Bakshi (2014) focuses on the energy consumption of dishwashers in the U.S., comparing a reusable option (ceramic cups) to a disposable option (EPS). Ceramic cups represent a “worst case” option among reusable cups with similar lifetimes (reusable glass cups and reusable PP cups). However, the authors conclude that the reusable cup has a lower environmental impact than the disposable option in most U.S. households, even with the oldest dishwasher model in use in the U.S. (from 2004). With the electricity consumption of a newer and energy efficient dishwasher model (2016), the environmental footprint of a reusable cup shrinks. The authors project that the environmental impact of the reusable option will decline even further in the future as the share of gas and renewables in the U.S. electricity mix increases and the majority of the environmental impact of the reusable system is in the electricity-intense washing process.

The study by Changwichan und Gheewala (2020) compares various disposable plastic cups (PLA, PP, and PET) with lids to a reusable stainless steel cup with a plastic lid. The reusable stainless-steel cup (washed by hand or in a dishwasher) has a lower GWP and fossil fuel consumption than the disposable options if it is used at least 140 times. Furthermore, stainless steel cups have the lowest impact on soil acidification and human toxicity when washed by hand. The authors conclude that washing the reusable option by hand results in a lower GWP than using a dishwasher. PLA cups have the lowest GWP among the disposable options, followed by PP and PET. The geographical region of the study is Thailand. Consumer behaviour has a strong influence on the frequency of a reusable cup’s use. The consumer may not want to use the same cup as often as needed to reach the break-even point. This is another reason why a low break-even point is important.

The environmental performance of reusable cups can be significantly higher if the reuse rate is assumed to be low. Vercalsteren et al. (2010) compare a reusable PC option with various disposable options (PP, paper with PE liners, and PLA) for an event serving. They assume that the loss rate of reusable cups is 12.5 % for large events and 5.5 % for small events in Belgium. They conclude that for large events, reusable cups are the worst option in terms of GWP and most of the impact categories due to the high replacement rate and energy consumption in the cleaning phase, and that disposable paper cups are the best option. For small events, reusable cups are the best option and disposable paper cups are the worst option with regard to the GWP and most of the impact categories.

2.3.3 Recyclability

Recycling disposable paper cups instead of sending them to landfill can reduce their environmental impact by 36 % (Foteinis 2020). The authors estimate that 1 in 400 paper cups is currently recycled in the UK. This is contrary to the waste hierarchy of the European Commission’s Action Plan for a Circular Economy. The rest of the plastic-lined paper cups end up in landfills or worse, as waste in the environment, contributing to microplastic pollution and other environmental problems.

Paper cups lined with a plant-based PE have a lower GWP than paper cups lined with fossil-based PE, and lower than paper cups lined with PLA due to recyclability benefits (VTT 2019). The fibers of a paper cup lined with a plant-based PE can be recycled up to seven times and thus more often than the other two (VTT 2019). However, only because it can be recycled does not mean it is currently recycled. Almeida et al. (2018) estimate a recycling rate for PE-lined paper cups of 21 % in Europe and 10 % in Australia and the United States.

Recycling of PLA cups leads to lower environmental impacts than anaerobic digestion and incineration (van der Harst et al. 2014). The authors also conclude that the recycling of PLA-coated paperboard cups results in lower environmental impacts compared to incineration, and that composting is the least preferable waste treatment for PLA and paperboard-coated PLA cups due to methane emissions and the fact that there are no credits associated with this treatment. If the cups are incinerated with energy recovery, they can receive credits for electricity generation.

The use of recycled content can reduce the environmental performance apart from the recycling rate. Increasing the use of recycled material by 25 % can decrease the environmental performance of a beverage cup by 35-56 %, as the study from Changwichan und Gheewala (2020) shows.

The end-of-life phase is a significant phase for single-use cups. In general, it can be said that the higher the recycling rate, the lower the climate impact. Even though recycling is the best disposal option for most materials and high recycling rates are recommended, in reality, recycling rates are relatively low in many countries, even for the paper cup (paper is a widely recycled material) (Foteinis 2020). As a matter of fact, the paper cup often does not end up in the recycling waste stream. Due to its use as a portable beverage cup, it often ends up in the residual waste garbage cans, the content of which either gets landfilled or incinerated. Even if the material is technically recyclable, it does not mean that it can be recycled. For example, PS for disposable cups and lids is widely used and technically recyclable, but recycling rates are low and few countries include PS in their recycling stream (UNEP 2021). The recycling of PS is associated with high costs and is often not considered profitable enough. The condition of the material can also lead to different waste treatment. For example, if a cup still contains remnants of organic material, it is more likely to be incinerated or sent to a landfill instead of being recycled.

2.3.4 Reusability

Whether a reusable cup performs better than a disposable cup largely depends on the frequency with which a reusable cup is used. The number of times a reusable cup must be used to reach the break-even point of a single-use alternative depends on its material and the material of the single-use option. A reusable PP cup must be used 21 times to be environmentally comparable to a disposable paper cup that is landfilled and 41 times to a disposable paper cup that is recycled (Foteinis 2020). In his study, Foteinis (2020) assumes a reusability rate of PP plastic cups of 500 uses for the UK.

In a study by VTT (2019), the authors conclude that a reusable ceramic cup must be used 350 times to reach the break-even point with a disposable paper cup. The rinsing phase accounts for 90 % of the emissions. In addition, the authors note that the ceramic cup never breaks, even if washing the ceramic cups is inefficient or if more than 80 % of the disposable paper cups are recycled after use. The authors use the circular footprint formula which grants partial credits in the recycling process for a saving in new materials that did not have to be produced. For reusable plastic cups, the authors estimate a necessary reuse rate of 20 times to reach the break-even point. If the single-use paper cup is recycled, the break-even point shifts to 32 uses for the reusable plastic cup. A reusable stainless-steel cup must be reused at least 130 times to reach the break-even point with the disposable paper cup.

In the study by Almeida et al. (2018), they conclude that a glass or PP cup needs to be used 24 times to be environmentally better than a PE-lined paper cup and 10 times to be better than a PLA-lined paper cup.

However, the washing method can also have an impact on the environmental performance of the reusable beverage cup. A stainless-steel cup washed by hand must be used 20, 40, and 70 times to have a lower GWP than a disposable PET, PP, or PLA cup (Changwichan und Gheewala 2020). A stainless steel cup cleaned in a dishwasher needs to be used about 100 times to have a lower GWP than a disposable cup made of PET, PP, or PLA, and it needs to be used 140 times to have all environmental impacts lower than the disposable options (Changwichan und Gheewala 2020).

The environmental performance of a reusable cup can be even further improved by using it multiple times between wash cycles (Martin et al. 2018; Woods und Bakshi 2014).

2.3.5 Summary

Comparing disposable cups, we can say that paper cups are ecologically comparable to recycled PET cups and have lower impacts than PS cups, while wax-lined paper cups have lower impacts than plastic-lined paper cups. PLA cups and PLA-lined paper cups do not necessarily perform better in environmental terms than fossil-based plastic options.

Recycling is the preferred end-of-life treatment in most cases. Although recycling is often possible, it is not carried out for reasons of cost, the general waste management system of the region, and consumer behavior.

The geographic context of the studies plays an important role, as technologies and energy use are region- and country-specific. While incineration with energy recovery is a widely used waste management treatment in Europe, landfilling is the dominant waste management option in other regions such as Asia. In particular, there is a lack of waste management in developing countries, with disposables ending up as waste in informal waste management systems. Recycling rates, which have a significant impact on outcomes, also vary around the world. Whether or not a cup is recycled frequently depends on its use and the conditions prevailing at waste disposal, too. For example, if a paper cup is contaminated with organic material, it is more likely to end up in an incinerator or landfill than being recycled.

For a reusable cup, the wash phase is the life cycle phase with the highest environmental impact, while for disposable cups it is the production phase. Using recycled materials to produce cups reduces the environmental impact of each cup, especially for disposable cups or for cups which require an energy-intensive production such as reusable stainless-steel cups.

In general, reusable cups have a lower environmental impact than disposable cups, although this is highly dependent on the number of uses a reusable cup needs to be better than a disposable cup. The losses of a reusable cup may be higher if the consumer does not own the cup. Most reusable cups need to be used 10-140 times to have a better environmental footprint than a disposable cup. On the other side, the littering potential of reusable cups is lower than that of disposable cups due to their higher weight. Among reusable cups, the PP cup has an environmental advantage over the ceramic cup and therefore needs to be reused less often to be comparable to disposable cups.

In the life cycle studies examined there is no clear preference for whether hand washing, or dishwasher rinsing is environmentally preferable for reusable cups. In general, it can be said that newer dishwasher models have a lower energy consumption compared to older models, and therefore are more environmentally friendly that washing by hand. However, if washing by hand is done using cold water, it may have a lower environmental impact than washing with dishwashers from older generations.

2.4 Take-away food packaging

Take-away food packaging systems are used to transport food from the restaurant to various consumption locations, such as customers' homes. They are also widely used in the food delivery sector. Take-away packaging can have different shapes and be made of different materials depending on the food being transported. Most of the food take-away packaging systems are single-use, but there are a rising number of reusable options. This chapter compares the different materials of single-use take-away packaging and their reusable alternatives.

2.4.1 Most common materials

Single-use plastic take-away packaging can be made from a variety of fossil-based plastics such as **PS, extruded polystyrene (XPS), PP,** and **PET**. They can also be produced from **bio-based plastics** such as **PLA**, or **bio-based raw material** such as **organic waste material** or **crops such as sugarcane or corn**, and **wood**. Single-use take-away packaging systems can also be based on other materials than plastic such as **paper or bamboo**.

Multilayer take-away packaging systems are packaging systems that are produced from different layers of materials. The different layers can **be fossil-based plastics, bio-based plastics,** or **non-plastic materials**, giving the packaging system a variety of properties.

2.4.2 Environment performance

The production of PLA can be an energy-intensive production process depending on the raw material which is used. PLA produced from bio-based waste material or isobutanol is preferable to PLA produced directly from fermented sugars. Single-use PLA products have no clear advantages compared to fossil fuel alternatives, which becomes evident when taking a closer look at the other product types. The study by Suwanmanee et al. (2013) concludes that PLA boxes have higher environmental impacts than PS boxes when electricity is modeled using the Thai electricity grid mix, the Thai coal grid mix, or Thai gas (Suwanmanee et al. 2013). In addition to GWP, the authors considered acidification and photochemical ozone formation. The PS boxes performed better than the PLA boxes in all three impact categories. The authors excluded waste management. If waste management were included, this would lead to even worse result for the PLA boxes, since waste management in Thailand is dominated by landfills. The disposal of PLA in landfills leads to methane and CO2 emissions. Emissions from land use change from corn and cassava are the largest contributors to the GWP of PLA (Suwanmanee et al. 2013).

Madival et al. (2009) compared different strawberry packaging systems made from PLA, PET and PS. They conclude that the transport phase of the packaging material is a large contributor to the environmental impact of the material. The results of this study are highly dependent on the distance assumed. The conclusion that the transport phase is an important contributor to the environmental footprint is in contrast to the results of Edwards und Fry (2011) and Khoo et al. (2010). In the study of Madival et al. (2009), PET packaging has the highest climate impact due to its heavier weight and the associated higher impact in the production and transport phase. PS packaging systems performed best in 7 out of 9 impact categories considered. PLA performs better only in the impact categories aquatic ecotoxicity and energy.

Johansson et al. (2019) compare three types of single-use multilayer food trays:

- FibreForm, which contains multiple layers of bio-based paper, laminated with multilayer films of PE, PA, ethylene vinyl alcohol copolymer (EVOH) and adhesives
- Multilayer of amorphous PET, PE, EVOH, polybutelene and adhesives
- EPS

The FibreForm tray is 85 % bio-based and paper is its main ingredient. The other two trays are fossil-based. All trays have a lid made from fossil-based material. The FibreForm tray outperforms the other two materials in all 4 studied environmental categories. The lower environmental impact follows from the lower impact of the production of the FibreForm trays compared to the others. The FibreForm tray also has a significantly lower GWP in the end-of-life phase compared to the other two. The advantages in the end-of-life phase of the FibreForm tray result from recycling. According to the authors of the study, FibreForm trays can be recycled in existing paper packaging recycling systems. Therefore 89.4 % of the FibreForm trays enter the recycling stream, while the other two trays are incinerated. There is no statement in the study on how the multilayer films made of PE and PA affect the recycling process of the FibreForm tray.

Evidence suggests that single-use paper-based take-away food packaging has a better environmental performance than some fossil-based alternatives. For instance, it has a better carbon footprint compared to PS and PLA, when waste treatment is landfill and the paper does not show decomposition due to its coating. However, if decomposition of the paper during waste treatment is taken into account, the paper alternative has a higher carbon footprint than PS but a still lower one than PLA packaging (Franklin Associates 2011). A major advantage of paper packaging is that its recycling is common practice in many countries, unlike the recycling of PLA or PS.

The study by Belley (2011) compares six different plastic boxes and one box made from recycled molded pulp (MP). They conclude that:

- trays made of XPS and MP have the best environmental performance and boxes made of PLA have the worst,
- the raw material and the production phase contribute most to the environmental impact of the trays,
- the plastic box made of 100 % recycled PET has comparable results to the XPS and MP in the impact categories of human health and aquatic eutrophication,
- XPS is not made of recycled material, but its low mass contributes to its good environmental performance.

The geographic region of the study by Belley (2011) is Quebec, with an electricity mix primarily based on hydroelectric power. The authors state that the results are sensitive to the type of electricity mix used in the production phase. However, changing the electricity mix does not change the conclusion that XPS and MP are the most environmentally friendly single-use options.

The study by Gallego-Schmid et al. (2019) compares three single-use take-away packages made from XPS, PP, and aluminum with a reusable Tupperware made of PP. The study concludes that:

- XPS has the best environmental performance among the single-use alternatives,
- the Tupperware must be used between 16 and 39 times to score better than the disposable XPS container in most impact categories,
- only for the impact category abiotic depletion potential of elements, the reusable Tupperware must be used 208 times,
- disposable aluminum and PP-based single-use Tupperware are the worst options,
- PP for single-use has the highest GWP and the highest primary energy demand,
- although XPS has the lowest environmental impact among the single-use options, it also has the highest littering potential due to its light weight, and
- XPS recycling is not a priority in most countries due to its high costs, which contributes to the littering potential of XPS.

Reusable PP take-away containers need to be reused 18 times to be better in terms of GWP than disposable take-away containers made of XPS (Gallego-Schmid et al. 2019). Baumann et al. (2018) reach similar conclusions: a reusable plastic container is environmentally better than a PS disposable container. A reusable plastic container for transporting fruits and vegetables is ecologically better than a disposable container made of wood, plastic, or cardboard (Accorsi et al. 2014).

An important factor not considered in most LCAs for take-away systems is how well a packaging system protects food (UNEP 2020b). This is important because the food protected in the packaging system often has a higher environmental impact than the packaging system around it (Notarnicola et al. 2017). Therefore, food protection should be a top priority for food packaging systems.

2.4.3 Recyclability

Recyclability plays an important role in single-use options. However, even if it is theoretically possible, this does not mean that recycling will be carried out in practice. For example, recycling XPS is theoretically possible but not carried out in practice due to the high costs involved. Instead, in most cases, XPS is incinerated or landfilled (Gallego-Schmid et al. 2019; Belley 2011). Another barrier to recycling take-away packaging is that contamination with food waste results in it ending up in residual waste rather than being recycled because consumers are more likely to throw the containers in the residual waste garbage can.

In a study conducted for the region of Canada, Belley (2011) assumes that PET boxes are made from 100 % recycled material, while the recycling rate is only 38 %. Similarly, MP is assumed to be made from 100 % recycled material, but only 41 % is recycled in the end-of-life phase. PLA boxes are assumed to contain 10 % recycled material, but 100 % of them end up in landfill. This shows that assumptions in the LCA studies are not always coherent with the real recycling practices. However, such assumptions are still justified in order to guide the decision-making towards facilitating higher recycling rates.

For recyclability, not only the material is important but also whether it is a single material or a multilayer material. It is easier for the recycling plant to recycle a pure material. For the recycling plants, it is often difficult to separate the different materials of a multilayer material. Therefore, in many cases, multilayer packaging is incinerated or landfilled instead of being recycled.

Another example of a hindrance for recycling is when PLA-based packaging is found in the waste stream. PLA has a negative impact on PET recycling. Most conventional sorting plants have problems distinguishing between PET and PLA. This results in a lower level of purification of the PET recyclate. Therefore, PLA is more likely to end up in landfills or incinerators instead of being sent to the preferred waste recycling (Benetto et al. 2015).

2.4.4 Reusability

The reuse rate plays an important role in reusable take-away packaging. A Tupperware made of PP needs to be used 16 to 208 times to be better than XPS, depending on the impact category and end-of-life management (Gallego-Schmid et al. 2019). For the impact category GWP, the reusable PP container must be used only 18 times to have a lower GWP than XPS (Gallego-Schmid et al. 2019). The reusable Tupperware made of PP needs to be used 208 times to be better than the XPS only for the impact category Abiotic Degradation Potential of Elements. For the other 10 impact categories, a reuse rate of maximum 39 is sufficient.

A reusable Tupperware out of PP has an environmental advantage compared to a Tupperware out of glass. The study of Gallego-Schmidt et al. (2019) concludes that a reusable glass food saver must be reused 3.5 times more often than a reusable PP food saver to be environmentally comparable. Here it is important to mention, that glass recycling is common practice in a lot of countries and LCAs do not include the risk of littering or microplastics, which are expected to be higher for the PP Tupperware.

2.4.5 Summary

It can be generally said that reusable plastic take-away food containers, such as reusable PP take-away containers, have a better environmental performance than single-use options. However, it needs to be ensured that they are reused often enough. There are different material options for reusable take-away containers. A container out of PP has advantages over the glass container due to the lower emissions during its production and due to its lighter weight. The glass container must be used 3.5 times as often as the PP container to be ecologically comparable with it.

Waste management is also closely linked to the geographic region and influences the environmental performance of packaging. For instance, single-use paper-based take-away food packaging has a better carbon footprint compared to PS and PLA, when waste treatment is landfill and the paper does not show decomposition due to its coating. However, if decomposition of the paper during waste treatment is considered, the paper alternative has a higher carbon footprint than PS but a still lower one than PLA packaging.

Although PS/XPS-based containers seem to have a lower environmental impact than other single-use material options, XPS is generally not recycled due to high costs. Thus, it is either incinerated or landfilled. Incineration with energy recovery is more common in Europe than in the United States, whereas landfill is more common in the United States and most Asian countries. Additionally, the light weight of XPS-based packaging also increases the risk of being picked up by the wind and ending up as litter.

Typically, the food inside the packaging has a larger environmental footprint than the packaging around it. Therefore, the main purpose of a take-away packaging system is to protect the food. If a material with a higher environmental footprint than another one protects the food in the event of food loss, it is still preferable in most cases. Multi-layered take-away food packaging can add a greater variety of properties to the packaging system, leading to better protection of the food. However, the use of multiple layers makes it difficult to recycle the materials.

PLA packaging for take-away food performs better than PET packaging for take-away food for most environmental impacts. However, PLA is difficult for most conventional sorting facilities to distinguish from PET, making it difficult to take advantage of preferential waste treatment recycling and composting. Instead, PLA is more likely to end up in landfills or incinerators.

The geographical region plays a major role in the environmental impact of a take-away packaging system. For disposable options, the production phase has the greatest environmental impact. The environmental performance of the production phase is directly linked to the energy mix used in the region. The same is true for reusable systems in the use phase of washing the container.

2.5 Meat packaging

Unlike the other packaging and drinking systems in this study, meat packaging has other tasks besides the purpose of transporting meat. The main purpose of meat packaging is to protect the meat from pathogens. Meat is often vacuum-packed to extend the shelf life of the meat. While other packaging systems such as take-away packaging systems or grocery bags are often used for a short period of time, meat packaging is designed to last over a period ranging from days to months. The packaging is designed to protect the meat so that it has a longer shelf life and is not thrown away. Most meat packaging is made of single-use fossil-based plastic. This chapter compares the different plastic materials and their alternatives.

2.5.1 Most common materials

Most of meat packaging systems are **single-use plastics** such as **XPS, PET, PP, PE,** and **polyamide (PA).** They can also be made from **bio-based plastics** such as **PLA** or using **multilayer and thermoformed film meat packaging** systems. Thermoformed film meat packaging is generally produced using a variety of material combinations, such as **PA/PE** and **PE/EVOH.**

2.5.2 Environment performance

In a study by Pauer et al. (2020), six different packages for a block of bacon were compared in terms of their environmental impact:

- two thermoformed film packages (PA/PE and PE/EVOH),
- two vacuum bags (PA and PE) and
- two shrink bags (PE/polyvinylidene dichloride (PVdC) and PA/EVOH/PE).

Pauer et al. (2020) conclude that the climate impact of the material mainly depends on the weight of the packaging material and the content of PA. Of the six materials studied, the shrink bag containing PVdC had the lowest carbon footprint and the thermoforming film containing PA/PE had the highest. Despite better recyclability of the PE/EVOH film, its climate change result was found to be considerably higher than the climate impact of the PVdC-containing shrink bag. Thus, in this case, a trade-off between better recyclability and climate benefit as a result of weight reduction, which comes at the cost of recyclability, becomes visible. Another study by Barlow und Morgan (2013) also emphasizes that reducing the material of the packaging material without reducing its protective capacity should be prioritized over improvements in recyclability. However, it is noteworthy mentioning that not all countries are equipped with modern waste incineration plants capable of filtering out toxic dioxins. Thus, combusting PVdC with suboptimal technologies could result in harmful emissions, thus diluting the environmental benefit. In such cases, using a heavier, but better recyclable packaging may be a better alternative.

On the other hand, the use of recycled material can significantly reduce the environmental impact of the packaging as the study of Maga et al. (2019) shows. However, the used recycled material has to comply with regulations for use in contact with food and especially meat.

A study by Maga et al. (2019) compared nine disposable meat packaging solutions for their environmental impact and concludes that:

- the light weighted XPS-based meat packaging had the lowest environmental impact and PLA had the highest,
- the PP container was the second-best material after XPS,
- the multilayer packaging solutions had a higher environmental impact than the solutions made of mono-materials, also due to their lack of recyclability,
- the carbon footprint of the PET box made from 100 % recycled material is 75 % less than that of a PET box made from 100 % virgin material, and
- PLA boxes scored worst in 10 of 13 impact categories. In the other three impact categories (resource depletion, climate change, and climate change when the biogenic carbon is excluded), the results from PLA were found to lie between the impact of other materials.

A study by Wikström et al. (2016) compares two single-use plastic meat packaging types: tube and tray. The tray is made of PET and has a plastic film out of LDPE and PET. The tube is made of PA. The tube weights around 80 % less than the tray and therefore uses less material. The results show that the tube has the better environmental performance, without considering customer behavior. However, it turns out that the easy-to-empty attribute of the tray has a significant impact on the results. Customers are not able to empty the tube packaging completely. The tube design of the packaging leads to higher food waste. Therefore, the tray has a better environmental performance than the tube packaging if the consumer behavior is included. In this case, the high environmental impact of the packaged meat is the decisive factor. On the other hand, the tube is better able to preserve the food inside for a longer period of time. This could shift the results in favor of tube packaging again.

In the study by Dilkes-Hoffman et al. (2018), the authors compared a biodegradable food packaging system (thermoplastic starch (TPS) and polyhydroxyalkanoate (PHA) layered material) with a fossil-based food packaging system out of PP. The biodegradable packaging system and the PP packaging system have similar carbon footprints in their production phase. The total carbon footprint of the biodegradable packaging system is highly dependent on waste disposal. If the waste disposal is a landfill with no methane recovery, the biodegradable packaging has twice the carbon footprint of the PP packaging. The carbon footprint of biodegradable packaging can be half that of the PP packaging system if the methane recovery rate at the landfill is 97 %. However, according to the authors, the average methane recovery rate in Australia is 30 % and therefore leads to a disadvantage of the biodegradable packing systems.

The environmental performance of meat packaging plays an irrelevant role compared to the overall environmental impact of the meat product (Heller et al. 2019). Optimal product protection should be a priority for packaging designers. Preventing food waste through packaging by extending shelf life has a greater environmental impact than reducing the environmental impact of packaging (Pilz 2017). Not all meat is sold wrapped in plastic. For example, a lot of meat is sold at deli counters. The freshly sliced meat, sausage, or ham is much more susceptible to microbial deterioration than meat packaged in single-use plastic packaging. Therefore, the material from the deli counter has relatively high loss rates (Pilz 2017).

As the production stage has the greatest impact on the environmental footprint of a single-use packaging system (excluding the packaged meat), the environmental footprint of a foamed PS tray for fresh meat can be reduced by 14 %, using renewable energy in the manufacturing process (Ingrao et al. 2015).

2.5.3 Recyclability

For food packaging, especially meat, there is concern about contaminants from the recycled plastic getting into the food. Recycled materials must comply with regulations for use in contact with food and especially meat.

In the study by Maga et al. (2019), a recycling rate of around 40 % is assumed for the recycled PP shell in a European context. No recycling was assumed for the shell made of multilayer material, recycled PET, XPS or PLA. Instead of recycling, the materials are either incinerated or landfilled. The recycled PET tray is assumed to be 100 % recycled material and due to the use of the recycled material, its carbon footprint is 75 % smaller than the carbon footprint of the 100 % virgin material tray.

The thermoformed film packaging (PA/PE and PE/EVOH) from the study by Pauer et al. (2020) is recyclable. However, despite its recyclable advantages, it has a higher carbon footprint than the PE/PVdC shrink bag.

2.5.4 Reusability

No reusable meat packaging was evaluated in the LCA studies reviewed.

2.5.5 Summary

There are no reusable options evaluated for meat packaging systems. The thickness and the weight of the packaging can be reduced to lower the environmental footprint of the packaging as long as the necessary food protection is provided. The use of recycled material can significantly reduce the environmental footprint of the packaging material. Furthermore, the post-consumer recyclability of the packaging can reduce the GWP of the packaging material.

Weight reduction of packaging in the context of multilayer packaging systems, leads to poor recyclability, but overall lower environmental impacts. However, the waste management option and the technology of the waste treatment option have a significant influence on the environmental impact. For instance, in countries where waste incineration plants that are not equipped to filter out dioxins, using heavier but recyclable packaging may be a better option.

In countries with mostly landfill treatment, presence or absence of methane recovery systems influence the environment impact of different packaging materials.

Furthermore, some packaging materials, such as XPS, show a low environmental impact, but are not recycled due to high costs, and are also more susceptible to littering due to light weight.

Due to low recyclability, multilayer packaging systems have a higher environmental performance than the solutions made of monomaterials. However, if the multilayer packaging design leads to a longer shelf life of the meat, it is environmentally preferable to mono-materials with a shorter shelf life of the meat.

The best environmental improvement of meat packaging is to extend the shelf life of the meat. For instance, on average, the packaged bacon has 54 times the carbon footprint of the packaging Pauer et al. (2020). Therefore, the protection of food should be the primary goal of packaging desgn. Tubing designs for meat may result in food wastes in the packaging. The food scraps in the packaging can lead to incineration and landfill instead of recycling the packaging material.

3 Aspects not entirely covered by LCA Studies

LCA studies try to represent the overall environmental footprint of a good. To do so, the reality needs to be simplified to a model. These simplified models do not represent the complexity of real-world systems. For example, LCA studies typically do not account for the concentration of hazardous substances and also lack a representation of the impact on biodiversity (UNEP 2020a).

Plastics can degrade to microplastics if they are not sent to the correct waste disposal system. The impact of microplastic on ecosystems is completely ignored in most LCA studies. Some LCA studies attempt to quantify the littering potential of materials, but this method is not widely used and is not an official impact category of LCA studies.

Even though biodegradable plastics degrade under certain conditions, these conditions are often not met in reality. However, LCA studies often simplify that biodegradable plastics are fully degradable or decompose like paper (Civancik-Uslu et al. 2019). They usually do not consider whether the conditions for full degradation are met or not.

This chapter concentrates on some of these impact categories that are left out in most LCA studies.

3.1 Hazardous substances

Shopping bags, beverage containers or cups, take-away food packaging and meat packaging are plastic items based on the most common materials specified in each section above. However, besides the polymer granulate or foil, their manufacture requires additional substances, i.e. additives, adhesives or coatings, auxiliaries[4], and other non-intentionally added substances.

In total, Groh et al. (2019) mention about 900 to 3000 chemicals that are likely to be associated with plastic packaging. The identified hazardous chemicals are used in plastics as monomers, intermediates, solvents, surfactants, plasticizers, stabilizers, biocides, flame retardants, accelerators, and colorants, among other functions. The authors present a database of chemicals associated with plastic packaging, which includes chemicals used during manufacturing and/or present in final packaging articles.

As to the hazards of these substances, Groh et al. (2019) found that of the 906 chemicals likely to be associated with plastic packaging, 63 rank highest for human health hazards and 68 for environmental hazards[5]. Furthermore, 7 of the 906 substances are classified in the EU as persistent, bioaccumulative, and toxic (PBT) or very persistent and very bioaccumulative, and 35 as endocrine disrupting chemicals. It should be noted that some of the substances can be attributed to more than one group of hazards.

Plastic packaging contains such substances irrespective of the material used, i.e. virgin, recycled or bio-based material (Geueke et al. 2018; Zimmermann et al. 2020). The study of Zimmermann et al (2020) investigates bio-based food-packaging, e.g. trays, coffee cups, tea bag wrappers. It was shown that these bio-based products contain similar amounts of chemicals as fossil-based plastics, including some with toxic properties. It was demonstrated that out of the 43 products, 29 contained chemicals that induced baseline toxicity, 18 that induced oxidative stress, and 11 endocrine effects[6].

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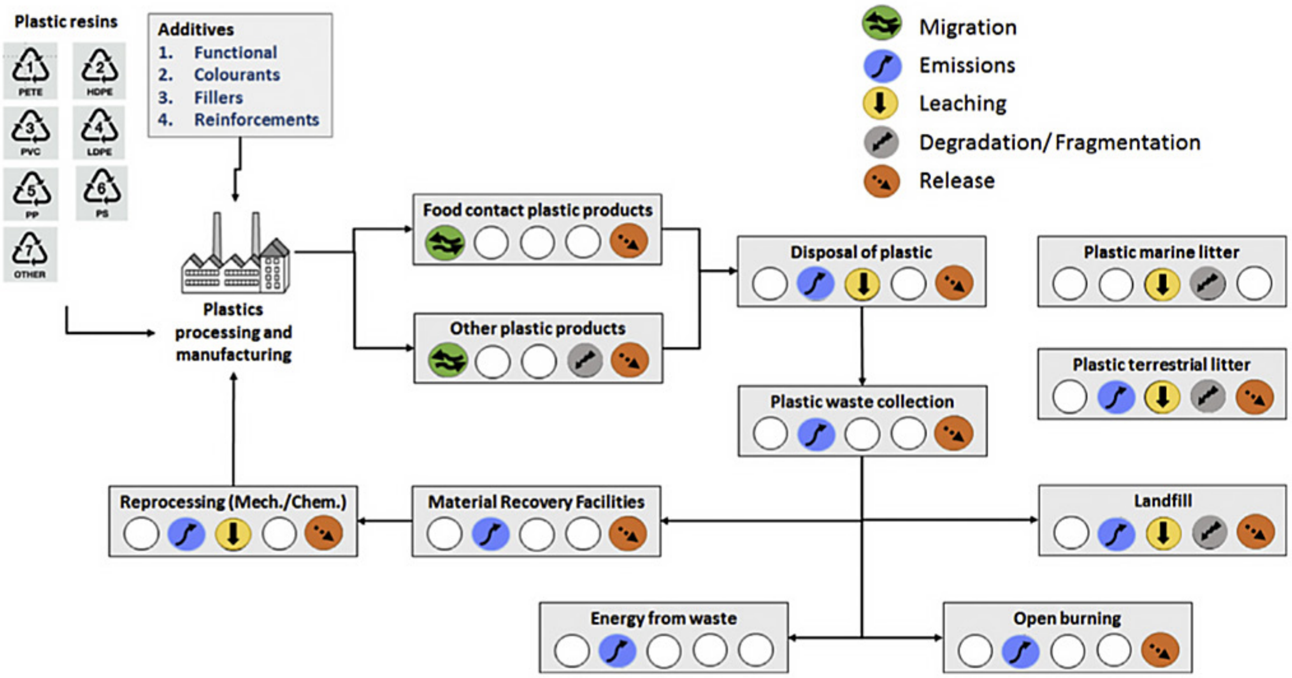
[4] Substances needed during manufacturing processes, e.g. solvents

[5] According to the harmonized hazard classifications based on the Nations' Globally Harmonized System (GHS)

[6] They found plastic additives, including butanediyldihexadecanamide, ethylenebis(palmitamide), erucamide and Irganox 1076, as well as non-intentionally added substances, including tetraoxacyclotetracosane-tetrone, a migrate from PE packaging and tris(2-nonylphenyl) phosphate (in Bio-PE), which is a degradation product of the antioxidant tris(nonylphenyl) phosphite (TNPP).

To evaluate the risk attributed to hazardous substances, in addition to their harmful characteristics (as assessed by Groh et al. (2019), the exposure scenarios have to be considered. Figure 3-1 presents the exposure and emission scenarios of hazardous substances from plastic during the life cycle. Five types of emissions into the environment can be differentiated: Migration into the packed material, emissions to the air, leaching into soil and aqueous environments, degradation, i.e. formation of microplastic, and the release.

Figure 3-1: Exposure scenarios for plastic additives along the life cycle of plastics



Source: (Hahladakis et al. 2018)

Some well-known examples of hazardous substances associated with packaging are described in the following:

- The group of polyflurinated alkyl substances (PFAS) is used in packaging foils and coatings of (single-use) plastic as well as cardboard tableware, cups and cutlery. PFASs accumulate in the human body because of their persistent character. These substances also accumulate in the environment without being degraded. The European Food Safety Authority (EFSA) suspects links between individual PFAS and reduced vaccination effects, lower birth weight, increased cholesterol levels and infections such as intestinal inflammation. However, many of the 4.700 substances have hardly been studied yet.

- Bisphenols, with Bisphenol A being the most famous representative of the group of bisphenols, are used as monomers in the manufacture of clear polycarbonate plastic, e.g. for cups or drinking water canisters and the manufacture of other plastic-related materials, including the lining inside food and drink cans. This group of chemicals has endocrine disruptive properties, and thus has effects on the human hormone system. BPA molecules can migrate into the beverages during use phase.

- Another group of substances is the phthalates, which provide a plasticising effect to the material. Some meat packaging and the sealing of screw caps contains phthalates. However, phthalates can also enter the food during production, e.g. when vegetable oil is pumped through flexible plastic pipes containing PVC. Some of the phthalates have adverse effects, however, in practice, the thresholds are not exceeded through diet-related exposure to phthalates.

- Polyvinyl chloride (PVC) is used in several single-use packaging applications such as labels of plastic bottles, transparent packaging boxes and trays[7]. PVC is particularly used because of its low price, durability, and scratch resistance. PVC as such has no adverse effect, however, in any end-of-life management option that involves thermal treatment under uncontrolled conditions (waste-to-energy, open burning, and reprocessing), it forms highly toxic fumes (containing hydrogen chloride, dioxins and furans). Therefore, PVC-waste is a particular concern in regions where proper management of plastic waste cannot be guaranteed.

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[7] Transparent PVC is hard to be distinguished from transparent PET, which is also used in many of these single-use applications. Identification is partly supported by the printed recycling code, where 1 stands for PET and 3 for PVC.

3.2 Microplastic & Littering

Single-use products are used only once before being thrown away. As a result, there is a higher risk of them ending up as waste in the environment than with reusable products. Consumer behaviour is different for single-use products than for reusable products. The additional use of a product makes the reusable option seem more valuable, leading to less careless disposal after use.

Reusable options are often more durable than disposable options and therefore heavier. The lighter a material is, the more easily it is picked up by the wind and therefore ends up in the environment as waste more readily (Civancik-Uslu et al. 2019). Single-use plastics are particularly lightweight. For example, PS and XPS have a low environmental impact in their production due to their lightweight construction, but they are associated with a particularly high littering potential (Civancik-Uslu et al. 2019).

Materials degrade at different rates when they end up as waste in the environment. While non-plastic materials such as paper and bamboo degrade after a certain time, fossil-based plastics and some bio-based plastics normally never fully degrade. When plastics do enter the environment, they remain there for a long time because of their stability and durability. Wind and water currents disperse the plastics over a wide area. Over time, abrasion and erosion create smaller and smaller fragments from larger pieces of plastic. These small pieces are called microplastics.

Ingestion of trash and plastic can cause physical harm and death to animals. Ingestion of microplastics introduces harmful chemicals into the food chain. Microplastics are found in all types of marine animals, from fish to birds and marine mammals (UBA 2013). The effect of the accumulation of microplastics in the food chain on the human health is still insufficiently researched.

3.3 Biodiversity and Land use

Bio-based plastics are not more sustainable than conventional plastics: Substitution of fossil-based plastic with bio-based plastic does not result in a significant improvement for the environment; instead, the impacts shift. In the study of Ita-Nagy et al. (2020) the authors analyze a number of LCAs that compare bio-based and fossil-based plastics. The authors conclude that “bioplastics generally show lower climate change impact than fossil-based plastics [...]. However, these materials also show higher burdens in environmental categories related to harvesting and cultivation of the raw biomaterials, including LCA categories associated with water, such as eutrophication, and air, such as stratospheric ozone depletion or photochemical ozone formation.” Similar trade-offs are also found in a variety of other studies (van der Harst et al. 2014; European Commission 2019; Papong et al. 2014).

Three additional problems regarding the material basis are:

- Due to challenges in modeling, **land use change** (LUC)[8] is a less assessed LCA category. Piemonte and Gironi (2011), however, 'highlight the strong influence of the LUC emissions on the GHGs saving achievable by displacing single-use petroleum-based plastics with bioplastics.' The same authors point out 'the importance of using waste biomass or biomass grown on degraded and abandoned agricultural lands to produce bioplastics that, in this manner, can offer immediate and sustained GHG advantages.' In the study of Suwanmanee et al. (2013) the authors detect land use change as the highest contributor to the GWP of bio-based plastics.

- Already known from the food-versus-fuel debate, a justifiable discussion is going on in terms of a **land use conflict**, i.e. whether the land is used to grow food or biomass, and whether the grown food, e.g. tapioca, is used for plastic production instead of nutrition.

- The authors of the impact assessment study for bio-based material (European Commission 2018) acknowledge that 'high yield of crops in Brazil and the US are a result of large-scale **monoculture** depending on genetically modified organisms (GMO) breeds with other adverse impacts which are not included in the LCA for methodological and data availability reasons.' In short, it can be concluded that monocultural cultivation including the uses of GMO breeds, fertilizers and pesticides results in **losses of biodiversity**, which are generally difficult to assess quantitatively.

In this sense, as concluded by Piemonte and Gironi (2011), plastic from agricultural waste, e.g. bagasse, palm leaves, mixed agricultural waste, should be preferred over bio-based material that could be used as food.

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[8] The EU Renewable Energy Directive (RED) defines direct land use change as "arising when the production of feedstock has led to a change from one of the following land cover, forest land, grassland, wetlands, settlements, or other land, to cropland or perennial cropland". Indirect land use change is defined as follows: "Where pasture or agricultural land previously destined for food and feed markets is diverted to biofuel production, the non-fuel demand will still need to be satisfied either through intensification of current production or by bringing non-agricultural land into production elsewhere. The latter case constitutes indirect land-use change […]".cited in European Commission (2018).

3.4 Real end of life scenarios of biodegradable plastics

Emissions during the end-of-life phase of an LCA strongly depend on the material and the type of waste disposal in question. For most single-use plastics, recycling is the best solution. However, biodegradable polymers are incompatible with many other polymers (e.g. polyolefins and PET). This causes problems for recycling plant operators, as the presence of biodegradable polymers in the recycling raw material acts as a pollutant and reduces the quality of the recycled polymers.

The most obvious solution for biodegradable plastics is therefore their degradation by composting. In life cycle assessments, the degradability of biodegradable plastics is often simplified and assumed to be similar to paper (Civancik-Uslu et al. 2019; Mattila et al. 2011). The number of biodegradable plastics that decompose under ambient conditions in different environments, e.g. home composter, marine water, etc., is very limited. Commercially used **biodegradable plastics require specific treatment** to decompose within a reasonable timespan of up to six months (industrial composting). In addition, it takes more time to decompose than other organic waste. This results in management problems for composting plant operators (Kunitzsch 2018). Moreover, their decomposition is not suitable for building up humus.

Both biodegradable plastics and bio-based plastics can be incinerated with energy recovery. However, the incineration of waste depends on the country's waste management. In Thailand and Malaysia, waste management is dominated by landfills (Lacovidou and Siew 2020).

In landfills, biodegradable plastics can cause methane emissions (European Commission 2019). A landfill without methane utilization leads to significantly higher environmental impacts for the biodegradable plastic (Dilkes-Hoffman et al. 2018; Civancik-Uslu et al. 2019). In the study by Papong et al. (2014), the authors conclude that the carbon footprint of a single-use bottle made from bio-based plastic can double if it is landfilled without methane recovery. If there is no methane recovery, waste incineration is the better solution for bio-based plastics (Mattila et al. 2011). It is noteworthy mentioning that landfills in developing countries are often just dump sites and are not managed in a controlled manner.

Biodegradable plastics have some distinct disadvantages (Brizga et al. 2020; Oakes 5 Nov 2019; EEA 2020; Burgstaller et al. 2018; DUH 2018b). Biodegradable plastic is often promoted as a solution to problems associated with the amount of plastic waste. At present, however, it does not reduce waste volumes nor problems associated with solid waste management.

For the public, the term "biodegradable" conveys the impression that plastic can be completely degraded – which is not true. Thus, the risk of consumers carelessly throwing the plastic into the environment, i.e. littering, and the risk of microplastic formation increase.

3.5 Comparing end-of-life scenarios

The best waste treatment is to produce no waste. In order to determine what kind of waste treatment to apply, the waste hierarchy can help. The five stages of the waste hierarchy describe what kind of waste treatment is preferred over another one (European Commission 2020).

1. Prevention
2. Preparing for re-use
3. Recycling
4. Recover
5. Disposal

The first two levels of the waste hierarchy can be achieved through reusable products, regardless whether they are directly reused, like shopping bags, or if they are prepared for reuse, like reusable cups that are washed before reuse. Neither of the single-use solutions meets the highest priority of the waste hierarchy, regardless of the material used. Alternatives to fossil-based plastics, such as bio-based plastics or paper, do not change this fact, as long as they are single-use products. The highest level for single-use options is the third tier.

In most LCA studies, recycling is considered the best available waste management option for singleuse products (European Commission 2019; Papong et al. 2014). However, recycling rates of countries are often not high enough to recycle all single-use products. In Thailand, the collected for recycling rate for PET packaging lies between 31 % to 62 % in 2019, while only 3 % of the PET packaging is recycled as food-grade rPET (World Bank 2021b). On the other hand, bio-based and biodegradable plastics cause problems in the recycling stream, as mentioned in chapter 3.4. For biodegradable and bio-based plastics, the last two levels of the waste hierarchy are the only possible waste treatments.

4 Conclusions and key implementation aspects

In the following, main conclusions of the study are drawn in order to support the decision-makers in Southeast Asia to consider meaningful and sustainable implementation aspects for packaging:

Substituting single-use products with other single-use products made from a different material is not an environmental-friendly option

No single-use product is better than the other in all environmental impact categories. There is just a burden shifting. For instance, single-use glass bottles perform worse than single-use plastic bottles in all environmental impact categories except eutrophication. Even a single-use paper bag, often perceived as an environmental-friendly alternative, performs worse in several environmental impact categories than single-use plastic bags. On the other hand, paper bags show a lower littering potential than single-use plastic bags. The use of bio-based PET instead of fossil-based PET can lead to a reduction in the global warming potential and fossil fuel consumption of a beverage bottle but may increase water consumption and eutrophication. Thus, although one single-use product may look environmentally preferable than another in a one-to-one comparison, all single-use products have a high burden on resource consumption.

Reusable products have a lower environmental impact than single-use products

Increasing the reuse rate of packaging products has the highest potential for reducing environmental impacts. Higher the reuse rate, lower the environmental impact. For instance, as the popularity of reusable shopping bags out of PP, PE and PET is increasing, they are found to be cost effective and in some cases only need to be reused few more times to have less impact on climate change than single-use plastic bags. Another example shows that switching to a reusable PP cup reduces greenhouse gas emissions considerably when compared to the disposable paper cup with landfill waste. Reusable PP cups also have an environmental advantage over the ceramic cup and therefore need to be reused less often to be comparable to disposable cup. However, if reuse rates of durable and reusable packaging are low, they do not perform better than the single-use products. The reuse rates from the different countries indicate that they are currently far below the break-even point that must be reached to be ecologically comparable to single-use packaging products. Therefore, high reuse rates need to be ensured and collection losses in the reverse logistics of reusable packaging minimized as much as possible. Furthermore, the littering potential of reusable cups is lower than that of disposable cups due to their higher weight.

Environmental burden of additional logistics, transportation and washing cycles for reusable packaging products does not reverse their environmental superiority over single-use products

Switching to a reusable system has a greater impact on the environmental performance of a beverage container than the distance it must be transported to the washing station. It has been found that reusable containers have a lower environmental impact than the disposable option, even after washing them with old dishwasher models. With increasing energy efficiency of dishwashers and increasing share of renewables in the electricity mix, the environmental footprint of a reusable container would shrink even further. In the life cycle studies examined there is no clear preference for whether hand washing, or dishwasher rinsing is environmentally preferable for reusable cups. In general, it can be said that newer dishwasher models have a lower energy consumption compared to older models, and therefore are more environmentally friendly than washing by hand. However, if washing by hand is done using cold water, it may have a lower environmental impact than washing with dishwashers from older generations. However, some reusable options, such as ceramic mug with lid, that are washed by hand

and with hot water have a higher environmental impact than disposable paper cups with PE liners and PS lids. It is noteworthy mentioning that the majority of the environmental impact of the reusable system is in the electricity-intense washing process.

Considering the challenges and technical limitations of recycling, it is more important to promote reuse than recycling

Increasing the reuse rate of packaging has a much higher environmental impact reduction potential than recycling. For instance, a bag's higher reuse rate has a bigger influence on its carbon footprint than its recycling rate. If reusable packaging products are made from post-consumer recycled material, the environmental impact reduction potential is even higher. However, it is known that collection and recycling rates are relatively low in many countries. Even if the material is technically recyclable, it does not mean that it is really recycled in practice. For instance, paper cups often do not end up in the recycling waste stream, but rather in the residual waste garbage cans, and hence, are either landfilled or incinerated. Another example is PS for disposable cups and lids. Although PS/XPS is technically recyclable, it is associated with high costs as well as high littering potential, leading to its escape from the recycling stream. Also, many shopping bag materials such as PP, HDPE, LDPE, or paper are recyclable. In practice, however, these bags are often not recycled.

LCA studies on single-use plastics and packaging do not adequately consider the impacts of hazardous substances, microplastic generation, littering, biodiversity loss and land-use changes. If these aspects are internalized, benefits of reusable products over single-use products would be even more obvious.

It is important to acknowledge the methodological limitations of LCA studies. While LCAs provide a good overview on several important environmental impacts, they do not show a complete picture. For instance, modelling of light-weight materials for single-use plastic products may result in lower climate impacts than that of reusable products made from more durable materials (including durable plastics). But light-weight single-use products are more susceptible to littering. In combination with hazardous substances and microplastic generation, they cause a severe threat to human health, marine & terrestrial environment, and biodiversity. Reusable products lead to a reduction in the overall material requirement and resource consumption. Hence, they cause a lower demand for land-use and extractive activities, thus avoiding land-use conflicts and monoculture plantations that trigger biodiversity losses. For instance, increasing the reuse rates for glass bottles or PET bottles leads to significant environmental benefits when compared to single-use glass or PET bottles.

Single-use packaging products made from bio-based plastic offer no advantages over other disposable plastic packaging products

Single-use packaging products made from biodegradable or bio-based plastics are just as short-lived and generate the same amount of waste as fossil-based options. As also mentioned above, there is only a burden shifting when fossil-based plastic packaging is replaced by bio-based plastic packaging. While conventional fossil-based plastics have a higher climate impact, bio-based plastics show a higher acidification and eutrophication potential. Additionally, they are associated with the land requirement, for instance, due to the agricultural production of the raw materials. This effect results in the competition for land with food production and also loss of forest areas leading to risks to the biodiversity. In general, plastic from agricultural waste, e.g. bagasse, palm leaves, mixed agricultural waste, should be preferred over bio-based material that could be used as food.

Advantages of biodegradable packaging are highly overrated and strongly dependent on the context

In ambient environment, e.g. home composter, marine water etc., the time required for decomposition is very long. Thus, biodegradable packaging does not solve the problem of littering. Under ideal conditions where collection rate of biodegradable packaging is very high, they still require specific treatment in an industrial composting plant to decompose within a reasonable timespan. Generally, they require more time to decompose than other organic waste, resulting in management problems for composting plant operators. Moreover, their decomposition is not suitable for building up humus, and thus, contradicts the whole purpose of producing organic fertilizers. On the other hand, biodegradable plastics cause sorting problems in the recycling process of fossil-based plastics. Most recyclers are not able to differentiate between bio-based and fossil-based plastics, which leads to quality degradation of the recycled material. For instance, PLA has a negative impact on PET recycling, leading to lower level of purification of the PET recyclate. Lastly, biodegradable plastics affect the Global Warming Potential in landfills much more than inert fossil-based plastics due to the release of methane in the composting process. In this regard, it is worth mentioning that landfills in most of the developing countries are uncontrolled and do not possess any methane recovery systems.

End-of-life management in a specific context has a significant influence on the environmental performance of a packaging material

There is no one-size-fits-all solution for the most appropriate waste management option for all packaging materials. If a country's waste management is mainly landfill, and the reuse rate of reusable packaging is low, recycled plastic packaging may be a better option for the climate. In countries where waste management is dominated by incineration – with or without energy recovery – cotton, paper and starch-based plastics may be better options for the climate. Single-use paper-based take-away food packaging has a better carbon footprint compared to PS and PLA, when waste treatment is landfill and the paper does not show decomposition due to its coating. However, if decomposition of the paper during waste treatment is considered, the paper alternative has a higher carbon footprint than PS but a still lower one than PLA packaging. On the other hand, the best waste treatment scenario for biodegradable PLA bottles is incineration with energy recovery, while for PET bottles it is recycling. Overall, it can be concluded that recycling has an environmental advantage over landfilling. However, after looking at the complex material-specific choices that need to be considered for selecting best possible waste management option, switching to a reusable system would not only be more practicable, but would also result in an even greater environmental benefit.

Environmental impact of a packaging is dependent on several factors, such as weight, size, use of mono-materials, recyclability, energy-mix of production processes and waste treatment option. These factors need to be analyzed on a case-by-case basis in order to evaluate the environmental performance of a packaging types and alternatives

From an ecological point of view, there is a clear preference for recyclable packaging options made from mono-materials. Furthermore, studies have shown that reducing the weight of the packaging has a positive influence on its environmental impact. In case of packaging based on mono-materials, easily recyclable components and availability of supporting collection and recycling infrastructure in the country, reduction of excessive and unnecessary packaging mass and volume has a high potential for reducing the environment impact. Even in case of a multilayer packaging comprising of a variety of materials, for instance, in order to ensure food hygiene and safety, a good collection system and treatment in modern incineration plants, would reduce the climate impact. However, in such a case, a trade-off between poorer material recyclability and immediate climate benefit needs to be addressed. It is known that higher rate of material recycling increases the amount of recycled plastics in the market, and if applied in the products, leads to climate benefits when compared with virgin plastics. It is also noteworthy mentioning that modern incineration plants are rare in developing countries. Hence, complex, non-recyclable packaging with potential low climate impact, could also lead to harmful emissions, for instance of dioxin, if treated in sub-optimal waste incineration plants. In such cases, using a heavier, but better recyclable packaging may be a better alternative. Heavier packaging weight, for instance for reusable options, may also have a smaller littering and microplastic generation potential.

In addition to the weight and material, the container size also plays an important role. For instance, due to the better ratio between packaging and beverage, a beverage in a larger bottle consumes less material per liter of beverage. Thus, larger bottles show a better environmental performance than smaller options. If the difference between two materials is not too great, changing the size of the container can change the order of the material performance. A similar concept to reduce the material per drink ratio is promoting reusable bottles.

For disposable options, the production phase has the greatest environmental impact. The environmental performance of the production phase is directly linked to the energy mix used in the region. The same is true for reusable systems in the use phase of washing the container. For instance, PLA boxes have higher environmental impacts than PS boxes when electricity is modeled using the Thai electricity grid mix, the Thai coal grid mix, or Thai gas. With an electricity mix primarily based on hydroelectric power, XPS based take-away package has the best environmental performance compared to other single-use alternatives, such as PP and aluminum. In such a case, a reusable PP container needs to be used between 16 and 39 times to score better than the disposable XPS container in most impact categories. However, XPS is related to the highest littering potential due to its light weight, and XPS recycling is not a priority in most countries due to its high costs.

Food packaging should be given a special attention in the debate on sustainable packaging solutions

An important factor not considered in most LCAs is how well a packaging system protects food. This is important because the food protected in the packaging system often has a higher environmental impact than the packaging system around it. Therefore, food protection should be a top priority for food packaging systems. Preventing food waste through packaging by extending shelf life has a greater environmental impact than reducing the environmental impact of packaging. Due to low recyclability, multilayer packaging systems have a higher environmental performance than the solutions made of monomaterials. However, looking from a narrower perspective, if the multilayer packaging design leads to a longer shelf life of the food product, it is environmentally preferable to mono-materials with a shorter shelf life of the meat. Putting a broader and systemic perspective on this topic, it will be important to question the meaningfulness of transporting fresh food products over long distances and storing them for extremely long shelf life. Instead, approaches for developing seasonal and regional food value chains for fresh, largely vegetable-based products with small distances, less storage requirements and immediate consumption will be important. Several LCA studies have clearly shown the environmental benefit of seasonal and regional food chains with a large vegetable share.

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Deutsche Gesellschaft für
Internationale Zusammenarbeit (GIZ) GmbH

Registered offices
Bonn and Eschborn

Friedrich-Ebert-Allee 32 + 36
53113 Bonn, Germany
T +49 228 44 60-0
F +49 228 44 60-17 66

Dag-Hammarskjöld-Weg 1 – 5
65760 Eschborn, Germany
T +49 61 96 79-0
F +49 61 96 79-11 15

I www.giz.de