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Doctoral Thesis

Sustainability Assessment of Packaging: a Holistic Approach Including Life Cycle Assessment, Circularity Assessment and Consideration of the Packaged Product

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Abstract

Packaging plays a central role in our economy. It enables the storage, transport and distribution of various products. Despite its indispensability in a modern economy, packaging is perceived as an environmental burden. Growing mountains of waste, plastic waste in the environment, climate change and the consumption of resources caused by packaging production have generated a lot of media attention for the topic of packaging sustainability. Public pressure and stricter regulations are forcing packaging manufacturers and distributors of packaged goods to make their packaging more sustainable. Packaging can be described as sustainable if it protects the packaged product in the best possible way, is produced as resource-efficiently as possible and is as circular as possible. Conflicts of interest can easily arise between these objectives. Methods for assessing packaging sustainability need to present all relevant sustainability indicators in order to avoid burden-shifting and to highlight potential conflicts of interest.

Life cycle assessment is a well-established assessment method. However, the great methodological diversity impairs the comparability and reproducibility of the results. Furthermore, in the past, the aspects of circularity and the interaction between the packaging and the packaged goods have usually been given little attention.

The aim of this doctoral thesis is to develop a holistic approach towards the assessment of packaging sustainability. A methodological framework for the assessment of packaging sustainability is proposed. The objective is to determine, which indicators best describe packaging sustainability, and how to calculate these indicators.

In a first step, an overview of existing methodological frameworks, guidelines and assessment tools is given. Then, the author developed a methodological framework for the assessment of packaging sustainability. The proposed framework defines three sustainability aspects of food packaging, namely direct environmental effects of packaging, packaging-related food losses and waste, as well as circularity. It provides a list of key environmental performance indicators and recommends certain calculation procedures for each indicator. The framework is oriented towards the Product Environmental Footprint (PEF) initiative and the Circular Economy Package of the European Union. This methodological approach is applied to a real life example.

A case study of multilayer plastic packaging for bacon was conducted. Six different types of multilayer films were analysed. Environmental impacts depend largely on packaging weight and on the content of polyamide. Only one of the packaging variants is recyclable. Nonetheless, the light-weight shrink bag performs better than the recyclable packaging which consists mainly of polyethylene. This highlights a potential conflict of interest between recyclability and resource efficiency. The environmental impacts of the packaged bacon by far exceed the environmental impacts of packaging, indicating that optimum food protection is the clear priority for ecodesign of meat packaging.

A detailed analysis was conducted to determine the influence of database selection on life cycle impact results of packaging. Different representative packaging systems were modelled using GaBi, ecoinvent and the Environmental Footprint database. While results for climate change are in the same order of magnitude, results for other impact categories often differ largely. This is mainly due to different data sources and modeling approaches by the databank providers. Errors in the databases as well as in the implementation of the Life Cycle Impact Assessment methods were detected. The use of the ecoinvent database leads almost always to higher results compared to GaBi.

As there is a growing demand for easy-to-use LCA tools, many online tools are offered. These so called S-LCA tools allow non-expert users to calculate the environmental impacts of packaging quickly. Important tools are PIQET, GaBi Packaging Calculator, and BEE. These tools are useful for ecodesign purposes, however user-friendliness and speed go at the expense of accuracy and flexibility.

In conclusion, the assessment of the environmental sustainability of food packaging has to take into account three aspects: Environmental impact of the packaging, circularity, and packaging related food losses and waste. The calculation of life cycle impacts of packaging should be oriented towards the PEF recommendations. The impact categories climate change, Respiratory effects, Acidification, and Water scarcity turned out to be in most cases among the most relevant impact categories for different packaging materials. Land use is an important indicator for biogenic materials, however the impact assessment method is associated with large uncertainties. Circularity assessment becomes more and more important due to regulatory requirements regarding recycled content and recyclability. Recyclability assessment should always take into account the existing collection and sorting infrastructure. Packaging related food losses and waste are highly relevant, but hard to quantify. A simplified approach is the Food-to Packaging ratio, which compares environmental impacts of the packaged food with the packaging. To obtain meaningful Life Cycle Impact Assessment results, the practitioner needs an excellent understanding of database quality issues as well as of Life Cycle Impact Assessment methods.

Kurzfassung

Verpackungen spielen eine zentrale Rolle in unserer Wirtschaft. Sie ermöglichen Lagerung, Transport und Vertrieb verschiedener Produkte. Trotz ihrer Unverzichtbarkeit in einer moderne Wirtschaft werden Verpackungen als Umweltbelastung wahrgenommen. Wachsende Müllberge, Plastikmüll in der Umwelt, Klimawandel und der durch die Verpackungsproduktion verursachte Ressourcenverbrauch haben für große mediale Aufmerksamkeit für das Thema Verpackungsnachhaltigkeit gesorgt. Öffentlicher Druck und verschärfte regulatorische Rahmenbedingungen zwingen Verpackungshersteller und Inverkehrsetzer verpackter Waren zu Bemühungen, ihre Verpackungen nachhaltiger zu gestalten. Als nachhaltig kann eine Verpackung dann bezeichnet werden, wenn sie das verpackte Produkt bestmöglich schützt, möglichst ressourceneffizient produziert wird und so zirkulär wie möglich ist. Zwischen diesen Zielsetzungen kann es leicht zu Interessenskonflikten kommen. Methoden zur Bewertung von Verpackungsnachhaltigkeit müssen alle relevanten Nachhaltigkeitsindikatoren darstellen, um Lastenverschiebungen zu vermeiden und potentielle Interessenskonflikte aufzuzeigen.

Die Ökobilanz stellt eine gut etablierte Bewertungsmethode dar. Allerdings beeinträchtigt die große methodische Vielfalt die Vergleichbarkeit und Reproduzierbarkeit der Ergebnisse. Außerdem wurden in der Vergangenheit die Aspekte der Zirkularität und der Wechselwirkung zwischen den Verpackungen und den verpackten Waren meist nur wenig beleuchtet.

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Ziel der vorliegenden Dissertation ist die Entwicklung einer Methode zur ganzheitlichen Nachhaltigkeitsbewertung von Verpackungen. Ganzheitlich bedeutet, dass neben den Umweltwirkungen der Verpackung auch noch Aspekte der Zirkularität und die potentiellen Umweltwirkungen des verpackten Gutes mitberücksichtigt werden. Ziel ist es, zu ermitteln, welche Indikatoren für Verpackungen relevant sind, und wie diese Indikatoren berechnet werden sollen.

Dazu wurde in einem ersten Schritt eine eingehende Analyse bestehender Bewertungsmethoden durchgeführt. Diese Methoden umfassen industrienahe Leitfäden sowie verschiedene Online-Tools zur Nachhaltigkeitsbewertung von Verpackungen. Großes Augenmerk wurde auch auf die europäischen Bemühungen zur Vereinheitlichung der Ökobilanzen im Rahmen der Initiative „Product Environmental Footprint“ gelegt. Auf Basis dieser Erkenntnisse hat der Autor methodische Empfehlungen entwickelt.

In einem zweiten Schritt wurde eine Fallstudie gemäß dieser Empfehlungen durchgeführt. Als Untersuchungsgegenstand dienten dabei Mehrschichtfolien für Fleisch. Die Umweltwirkungen sind weitgehend vom Gewicht der Folien und vom Polyamid-Anteil abhängig. Eine einzige Folie konnte als recyclingfähig eingestuft werden. Allerdings schneidet sie in der Ökobilanz selbst bei optimistischen Annahmen zur Recyclingquote schlechter ab als die leichteste, aber nicht-recyclingfähige Variante. Der verpackte Speck weist im Mittel etwa 50 mal höhere Treibhausgasemissionen auf als die Verpackung selbst.

Schließlich wurde eine eingehende Analyse verschiedener Ökobilanz-Datenbanken durchgeführt. Dazu wurden verschiedene Verpackungen modelliert und mit denselben Annahmen, derselben Allokationsmethode und den selben Auswertemethoden berechnet. Dabei wurde jede dieser Verpackungen dreimal modelliert, und zwar mit der GaBi Datenbank, der ecoinvent3.6 Datenbank und der Environmental Footprint Datenbank. Während die Ergebnisse für die Kategorie „Klimawandel“ relativ gut vergleichbar sind, trifft das auf andere Wirkungskategorien nicht zu. Die ecoinvent3.6 Ergebnisse waren fast durchgehend deutlich höher als die anderen, und zwar unabhängig vom untersuchten Verpackungssystem und den ausgewerteten Umweltwirkungskategorien. Die teilweise beträchtlichen Unterschiede bei den Ergebnissen haben mehrere Gründe. Die unterschiedlichen Datenbankanbieter modellieren die Datensätze recht unterschiedlich. Außerdem wurden einige offensichtliche Fehler entdeckt.

Zusammenfassend kann gesagt werden, dass sich die Ökobilanzierung von Verpackungen an den methodischen Empfehlungen des „Product Environmental Footprint“ orientieren soll, da so die Vergleichbarkeit und Reproduzierbarkeit verbessert werden. Bei den zahlreichen Analysen, die durchgeführt wurden, haben sich folgende Umweltwirkungskategorien als besonders relevant für Verpackungen herausgestellt: Klimawandel, Versauerung, Feinstaubemissionen und Wasserverbrauch. Bei biogenen Verpackungsmaterialien spielt der Landverbrauch eine große Rolle. Wesentliche Indikatoren zur Bewertung der Zirkularität sind der Anteil erneuerbarer Ressourcen, der Rezyklatgehalt, die Kompostierbarkeit, Recyclingrate, Recyclingfähigkeit und Wiederverwendbarkeit. Bei der Recyclingfähigkeitsbewertung muss zwischen Sammlung, Sortierung und stofflicher Wiederverwertung differenziert werden, da etliche Verpackungen zwar theoretisch stofflich verwertbar wären, aber mangels getrennter Sammlung in der Praxis verbrannt oder deponiert werden. Das verpackte Produkt soll in die Betrachtung miteinbezogen werden. Idealerweise sollten die Umweltwirkungen der verpackungsbedingten Lebensmittelabfälle ermittelt werden, und der Verpackung zugerechnet werden. Da dieser Wert aber sehr schwer ermittelbar ist, wird die

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Berechnung der Food-to-Packaging ratio als praktikabler Kompromiss empfohlen. Da die analysierten Ökobilanz-Datenbanken alle sowohl Stärken, als auch Schwächen haben, und die Anbieter sie ständig verbessern, wird an dieser Stelle auch keine eindeutige Empfehlung für eine bestimmte Datenbank ausgesprochen. Allerdings macht die Analyse klar, dass sinnvolle und interpretierbare Ökobilanz Ergebnisse nur dann erzielt werden können, wenn der Ökobilanzierer fähig ist, die Qualität der verwendeten Daten einzuschätzen und exzellente Kenntnisse über die verwendeten Wirkungsabschätzungsmethoden hat.

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Abbreviations

CF	Characterisation factor
EC	European Commission
EP	European Parliament
EVOH	Ethylene vinyl alcohol
FTP ratio	Food-to-Packaging ratio
GWP	Global Warming Potential
LCA	Life Cycle Assessment
PA	Polyamide
PE	Polyethylene
PEF	Product Environmental Footprint
PET	Polyethylene terephthalate
PP	Polypropylene
PVdC	Polyvinylidene chloride
S-LCA	Streamlined/Simplified LCA

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Published articles and contributions

This cumulative thesis is comprised of the following three journal articles:

Paper I Pauer E, Wohner B, Heinrich V, Tacker M. Assessing the Environmental Sustainability of Food Packaging: An Extended Life Cycle Assessment including Packaging-Related Food Losses and Waste and Circularity Assessment. Sustainability 2019. Volume 11 [1]

I have provided the following contributions to this paper:

- Conceptualization
- Methodology
- Investigation
- Writing
- Visualization

Paper II Pauer E, Gabriel V, Krauter V, Tacker M. Sustainability of flexible multilayer packaging: Environmental impacts and recyclability of packaging for bacon in block. Cleaner Environmental Systems 2020. Volume 1 [2]

I have provided the following contributions to this paper:

- Conceptualization
- Methodology
- Investigation
- Calculations
- Writing
- Visualization

Paper III Pauer E, Wohner B, Tacker M. The Influence of Database Selection on Environmental Impact Results. Life Cycle Assessment of Packaging Using GaBi, Ecoinvent 3.6, and the Environmental Footprint Database. Sustainability 2020. Volume 12 [3]

I have provided the following contributions to this paper:

- Conceptualization
- Methodology
- Investigation
- Calculations
- Writing
- Visualization

The above listed papers are submitted for the fulfilment of the requirements for a cumulative thesis. Additionally, the following article is included:

Pauer E, Heinrich V, Tacker M. Methods for the Assessment of Environmental Sustainability of Packaging: A review. IJRDO – Journal of Agriculture and Research 2017. Volume 3 [4]

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1 Introduction

1.1 Packaging and sustainability

Packaging plays a central role in our economy. It protects products, enables the transport of sensitive goods and also fulfils an important communication function. Different materials are used for the production of packaging. Without adequate packaging, there would be much more food waste. Packaging enables an efficient supply of high-quality food to the population. Therefore, packaging contributes significantly to sustainable development.

On the other hand, the growing amount of packaging used consequently leads to an increase in packaging waste. Since there are only inadequate disposal systems in many places, packaging waste is far too often disposed of in nature. Especially plastic waste in the oceans has made headlines in recent years. Although the contribution of European countries to so-called "marine litter" is comparatively small, the situation in Europe is nevertheless not satisfactory [5].

The consumption of resources associated with the production of packaging is also perceived as a problem by the public. For example, primary aluminium is needed for many types of packaging, which is associated with problematic bauxite mining in countries such as Brazil. The production of plastics is largely dependent on the extraction of oil and natural gas. Although this consumption of resources is by no means negligible, it is rather low compared to other industries (e.g. food production, construction). The same applies to the greenhouse gas emissions caused by packaging. They are also often cited as an argument for reducing packaging, although the CO_2 emissions caused by packaging are usually low compared to the emissions caused by the packaged product [6].

1.2 Definition of Sustainability

The term sustainability originates from forestry, and originally referred to the principle of only taking as much from the forest as can grow back again. The United Nations Brundtland Report defined sustainable development as development that meets the needs of the present without compromising the ability of future generations to meet their own needs [7]. The three-pillar model of sustainability assumes that in addition to environmental sustainability, social and economic sustainability must always be taken into account.

In the context of the present work, the term sustainability refers exclusively to the ecological, but never to the social and economic sustainability of packaging. When sustainability is mentioned in the following, ecological sustainability is always meant. In this sense, the use of the term refers to the original meaning: sustainable management means that nature must not be overexploited.

1.3 Definition of Packaging Sustainability

Verghese et al. define four basic principles of sustainable packaging [8]. Packaging should fulfil the following criteria:

- Effectivity
- Efficiency
- Safety

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- Circularity

Effectiveness means that the packaged product is protected in the best possible way and that the other packaging functions are also adequately fulfilled. Food losses can also be caused by inadequate packaging. Since the environmental impacts caused by food production usually exceed the impacts of packaging, even small packaging-related food losses can lead to relevant environmental impacts. Effective packaging must protect the packaged food from mechanical damage as well as from chemical and microbial spoilage. In addition, ease of use is also important, as poor emptying or resealability can lead to food losses. Appropriate sizing of packaging is crucial, as too large packaging can lead to consumers throwing away food.

Efficiency means achieving these goals with the least possible resource consumption and environmental impact. Measures to increase packaging efficiency include, for example, weight reductions or optimisation of manufacturing processes.

Safe packaging is free of harmful substances and does not pose any risk of injury. It must not impair human health. Since this dissertation is concerned with the environmental sustainability of packaging, this aspect will only be addressed insofar as it concerns pollutants that are released into the environment.

Circular packaging is made from recycled material or renewable resources and is reusable, recyclable or compostable. Circular packaging is characterised by closed material loops and renewable energy flows [9].

1.4 Measures to improve Packaging Sustainability

All these issues have led to great public pressure to make packaging more sustainable. At the EU level, several directives have been adopted to work in this direction. Directive (EU) 2018/852 amending Directive 94/62/EC on packaging and packaging waste [10] increases the pressure on member states to recycle more packaging waste. Of particular significance is the increase in the recycling rate for packaging plastics to 55% by weight by 2030. Companies that place packaged products on the market are obliged to participate financially in participation schemes as part of producer responsibility. These participation schemes organise the collection and recovery of packaging waste. Directive (EU 2019/904) on reducing the impact of certain plastic products on the environment (Single Use Plastics) [11] requires that plastic bottle caps must be permanently attached to the bottle to prevent them from ending up in the environment. A ban on placing expanded polystyrene food packaging on the market will apply from 2021. PET bottles must have a recycled content of at least 30% from 2030.

Apart from the EU requirements, the member states are may go beyond these requirements in their national legislation. For example, several states have mandatory one-way deposit systems for beverage packaging. The fees for the mandatory participation system can also be used to incentivize the use of recyclable packaging. In some member states, the fees for demonstrably recyclable packaging are lower than those for packaging that is difficult to recycle [12].

In addition to the legal requirements, there are numerous voluntary initiatives aimed at reducing the environmental impact of packaging. The influential Ellen MacArthur Foundation, whose "New Plastics Economy Global Commitment" [13] has been signed by numerous large companies and government institutions, is particularly worth mentioning here. This voluntary commitment stipulates that all packaging must be either recyclable, reusable or compostable by 2025.

In the political-media discourse, the focus is on increasing recycling rates and eliminating visible packaging waste in the environment. Public pressure and legislation in this regard also mean that sustainability assessment methods are becoming increasingly important.

1.5 Assessment of Packaging Sustainability

The methods of sustainability assessment include life cycle assessment, circularity assessment and the inclusion of the packaged product in the sustainability assessment of the packaging. The corresponding methods are presented in detail in chapter four.

LCAs have played a major role in the packaging sector for quite some time. The first LCAs ever were carried out in the late 1960s and early 1970s for beverage packaging [14]. The clients at that time were the EPA (Environmental Protection Agency) and Coca-Cola. Packaging LCAs can have far-reaching political and economic consequences. The study on different beverage packaging commissioned by the German Federal Environmental Agency was the basis for the introduction of a mandatory deposit for aluminium cans, PET and one-way glass bottles. Composite beverage cartons were exempted from the mandatory deposit because the study identified them as "ecologically advantageous" [15].

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2 Problem statement

Although LCA is a well-established and recognised tool for assessing the sustainability of packaging, there is still a great need for research and development. In the following, the problem areas addressed in the present work are named.

2.1 Exclusive focus on one single indicator

Since the discourse in recent years has revolved around climate change, many manufacturers argue that their packaging is particularly climate-friendly. For example, manufacturers of paper and bioplastic packaging like to refer to the relatively low CO_2 emissions, but conceal the high land consumption in the provision of raw materials. Manufacturers of aluminium cans advertise the excellent recyclability of the cans. However, this industry is also dependent to a certain extent on primary aluminium, the production of which is associated with environmental damage. Focusing on a single indicator always carries the risk of burden shifting: improvement in one area can lead to deterioration in another.

2.2 To many indicators

The problem described above has been known for a long time, which is why ISO-compliant LCAs always evaluate several environmental impact categories. This approach also involves certain risks, because listing the results for 10 different impact categories creates confusion and can lead to a situation in which only climate change is considered.

2.3 Presentation of irrelevant or redundant environmental indicators

Not every environmental issue is equally relevant for every type of packaging. For example, while land use is a relevant issue for bio-based packaging, this is not the case for plastic packaging. Ozone depletion is an important issue, but the packaging industry does not contribute to it to any relevant extent. The issue of redundancy is also important. The environmental impact category climate change is part of every LCA for good reasons. Many other impact categories (e.g. consumption of fossil resources, summer smog formation, etc.) correlate strongly with greenhouse gas emissions. Such redundant indicators do not provide any additional knowledge [16].

2.4 Methodological diversity makes comparability difficult

Despite the standardisation (ISO 14040/44) [17], there is great methodological diversity. Different system boundaries, different allocation methods and different evaluation methods may lead to different results for one and the same product. Since all data are rarely available completely and in good quality, it is often necessary to work with assumptions. Secondary data from LCA databases are used in addition to primary data from the manufacturer. There are several providers of such databases. The differences in quality as well as timeliness are often considerable. All this leads to the widespread criticism that by "clever" choice of method and secondary data the results can be turned in the direction desired by the client.

Something similar applies to the assessment of circularity. It makes a big difference whether packaging could only theoretically be recycled or whether there is actually a functioning collection, sorting and recycling system. The claim "made from renewable raw materials" or "bio-based" can also be misleading. This is because a biological resource can only be described as renewable if it comes from certified sustainable cultivation. If something is "bio-based", it does not necessarily have to be "renewable" - and certainly not "sustainable" [18].

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3 Aims and structure of the thesis

3.1 Approach

The aim of this work is to develop a holistic method for assessing the environmental sustainability of food packaging. Holistic means that all important aspects of packaging sustainability are covered so that there is no shifting of burdens. Conflicts of interest should not be concealed, but rather highlighted. At the same time, the focus should be on the really relevant indicators.

In addition to the selection of indicators, however, it is equally important to identify a reliable, reproducible assessment methodology.

3.2 Research questions

The present doctoral study aims to answer two questions:

1. Which indicators best characterise the sustainability of packaging?

2. How should these indicators be calculated?

Such a method should follow the principle of "as much as necessary, as little as possible". This is because sustainability assessments are primarily aimed at decision-makers in politics and business, as well as the interested public. Therefore, complexity should be reduced - where possible - without obscuring relevant conflicting goals and uncertainties.

The importance of this research question is derived from the high importance of the topic and the above-mentioned problems.

3.3 Scope

This thesis mainly focusses on food packaging in Europe, however, the main findings are applicable to non-food packaging as well as to different geographies.

4 Methods

4.1 Testing of different assessment tools & databases

In spring 2017, the author systematically explored assessment tools for packaging. Most of these programmes are online tools that can be operated via a web browser. These programmes are usually relatively easy to use and are intended to allow companies to carry out simplified life cycle assessments for their packaging at low cost. Since most of these programmes are chargeable, demo versions were tested. The scope (packaging materials, regionalisations), the user-friendliness and the environmental impact categories that can be evaluated were examined during testing.

Simplified, representative packaging systems were calculated using three different databases. The same impact assessment method was also always applied. The sometimes considerable differences in the results for the same packaging were analysed by tracing which processes and which flows contribute to the differences. Furthermore, it was examined whether the impact assessment method was always implemented correctly.

4.2 Development of a methodological framework for the assessment of packaging sustainability

An extensive literature search was conducted to obtain an overview of existing assessment methods. The focus was clearly placed on practical systems used by the industry. Furthermore, intensive research was carried out for scientific literature on the topic. Google Scholar was predominantly used for the literature search. Based on the findings obtained through the research work, a recommendation was developed that both suggests the relevant indicators and describes the methodology for calculating these indicators.

4.3 Case study: Assessment of existing packaging

Based on the methodological recommendation, a concrete practical example was calculated. Multilayer films for meat were selected for this purpose. An LCA was carried out for these films based on the ISO 14040/44 standards and the recommendations of the European Commission for calculating the "Product Environmental Footprint" (PEF) [19]. In addition to the life cycle assessment, an evaluation of the recyclability of these films was carried out. The environmental impacts of the packaged product were also included in the assessment.

4.4 Life Cycle Assessment

Life cycle assessment (LCA) is the widely accepted method for assessing the potential environmental impacts of products and processes. The ISO standards 14040 and 14044 lay down the general rules for carrying out an LCA. The basic principle is to consider a life cycle as a sequence of interrelated processes (see Figure 1).

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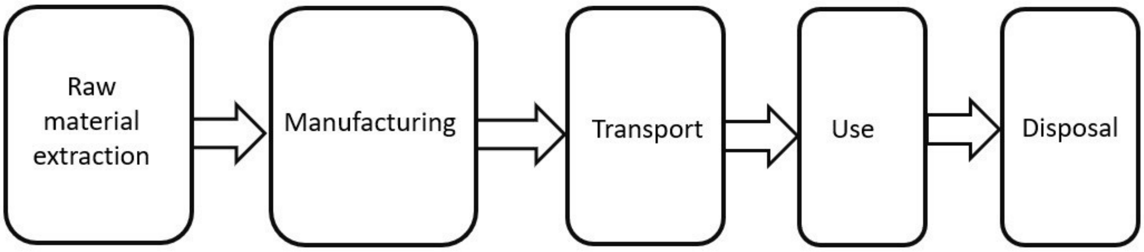

Figure 1: Schematic life cycle, from cradle to grave. Boxes represent processes, and arrows represent flows.

Each process converts inputs into outputs. The inputs are raw materials, energy or intermediate products, the outputs are products, waste and emissions (see figure 2). The inputs and outputs are referred to as flows in the LCA.

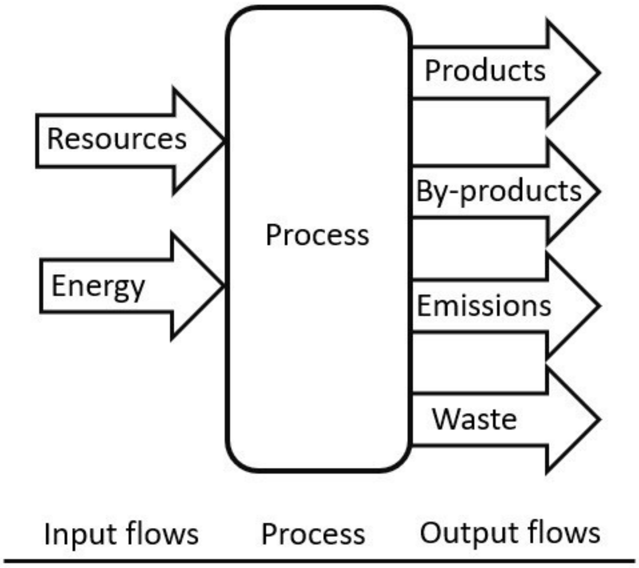

Figure 2: A process converts inputs in outputs

The compilation of these data (input and output flows) constitutes the life cycle inventory. The life cycle inventory documents the material and energy flows, but does not yet make any statement about the potential environmental impacts. The next step in a life cycle assessment is the impact assessment. Here, the flows (e.g. emissions) are converted into environmental impacts by means of characterisation factors. The environmental impacts are expressed by certain indicators. This is illustrated by the example of climate change results for a product: The life cycle inventory result is 2 kg CO_2 and 2kg CH_4 emissions. The indicator for the impact assessment method GWP100 (Global Warming Potential, 100 years) is the increase in radiative forcing in the atmosphere and is expressed in the unit kg CO_2 equivalents. The characterisation factor for CO_2 is 1, as it is the reference substance. The CF for methane is 37, since methane increases radiative forcing 37 times more than CO_2. The result of the impact assessment is therefore 2x1 + 2x37 = 76 kg CO_2 equivalents.

Despite standardisation, methodological diversity is a problem. The ISO 14040/44 standards define a general framework for LCA, but they allow for a great flexibility. Important methodological choices, eg. End-of-Life allocation or Life Cycle Impact Assessment method, are left to the practitioner. These methodological choices have a large influence on results, therefore comparability and reproducibility

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are often not given. The current proliferation of differing methods to assess the environmental performance of products leads to mistrust in environmental performance information and may increase cost for business.

The PEF initiative of the European Commission aims at a stronger harmonisation of LCA calculations. Mandatory footprint information on products would influence consumer behaviour and support sustainable purchasing decisions. Such an approach would require a high degree of standardization of calculation procedures to allow for a fair comparison. As a result of this, the EU member states and industry requested the European Commission to develop a standardized European method for the calculation of the environmental footprint of products and organizations. The PEF recommendations include the “Circular Footprint Formula” for calculating environmental burdens and benefits from the use of recycled materials as well as from end-of-life recycling of the product under investigation. This allocation formula fairly credits the use of recycled materials as well as end-of-life recycling, and also takes into consideration the issue of downcycling. Therefore, the “Circular Footprint Formula” overcomes the problems associated with other allocation procedures. The PEF initiative developed a list of sixteen recommendable impact assessment methods covering a wide range of potential environmental impacts. Moreover, the European Commission aims at the release of a database including recommended data sets for PEF compliant studies. At the time of publishing, a first version of the Environmental Footprint Database was already available. A harmonized approach can gradually improve comparability, but not provide full and fair cross-study comparability. Reproducibility and cost reduction will be achieved by reducing the number of methodological choices. Taken together, these arguments underline the importance of developing a harmonized European LCA approach, although there are still unresolved issues [20].

4.5 Circularity Assessment

The concept of the circular economy was popularised by the Ellen MacArthur Foundation and has found its political-regulatory expression in the EU's Circular Economy Package [21]. Companies need to improve the circularity of their products and are accordingly interested in meaningful indicators. These indicators relate to the use of secondary materials on the input side and to the recyclability or reusability of the products on the output side.

A circular economy is characterised by closed material cycles and renewable energy flows. In material cycles, a distinction is made between biological and technical cycles. Accordingly, circular packaging is produced from recycled or bio-based raw materials, and is recycled, composted or ideally reused after use. It is produced using renewable energy and contains no toxic substances. The technical cycles can be described by indicators such as recycled content, technical recyclability, actual recycling rate and reusability. The biological cycles are described by the share of renewable raw materials as well as by compostability. It is important to understand that bio-based raw materials are not automatically renewable raw materials. Marine fish from overfished stocks or tropical wood from virgin forests are undoubtedly biobased resources, but by no means renewable ones. In the sense of the circular economy, the use of biobased materials is only possible if no more is extracted than can also grow back. Renewable energy flows can be described by the share of renewable energy in the total energy consumed over the life cycle of the product. The Ellen MacArthur Foundation developed the Material Circularity Indicator, which combines input- and output-related values like recycled and renewable content, reuse rate, and recyclability into one single score indicator. A value of 0 indicates a completely linear product life cycle, while 1 means that a product is perfectly circular [22]. Table 1 gives an overview of indicators to describe a product’s circularity.

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Table 1: Circularity indicators for packaging

	Indicator	Metric	Comment
Input related	Recycled content	%	
	Renewable content	%	Note the difference between "biobased" and "renewable". Only sustainably sourced biobased material can be accounted for the renewable content.
Output related	Recyling rate	%	Mass percentage of a packaging material, which actually enters a recycling facility (See Directive 94/62/EC, Article 6a)
	Recyclability	%, Scale, expert judgement	Different approaches exists, nonetheless, an recyclability assessment should always differentiate between collection, sortability and material recovery.
	Compostability	Yes/No	Compliance with EN 13432 [23]
	Reuse rate	Number of usages	
Aggregated	Material Circularity Indicator	Value between 0 and 1	Ellen MacArthur Foundation, 2019

4.6 Consideration of the packaged product

An essential aspect of packaging sustainability is the best possible protection of the packaged product. Food losses and waste are a serious environmental concern and – in some cases – packaging related. Ideally, the environmental impacts of packaging-related product losses should be allocated to the packaging (see figure 3).

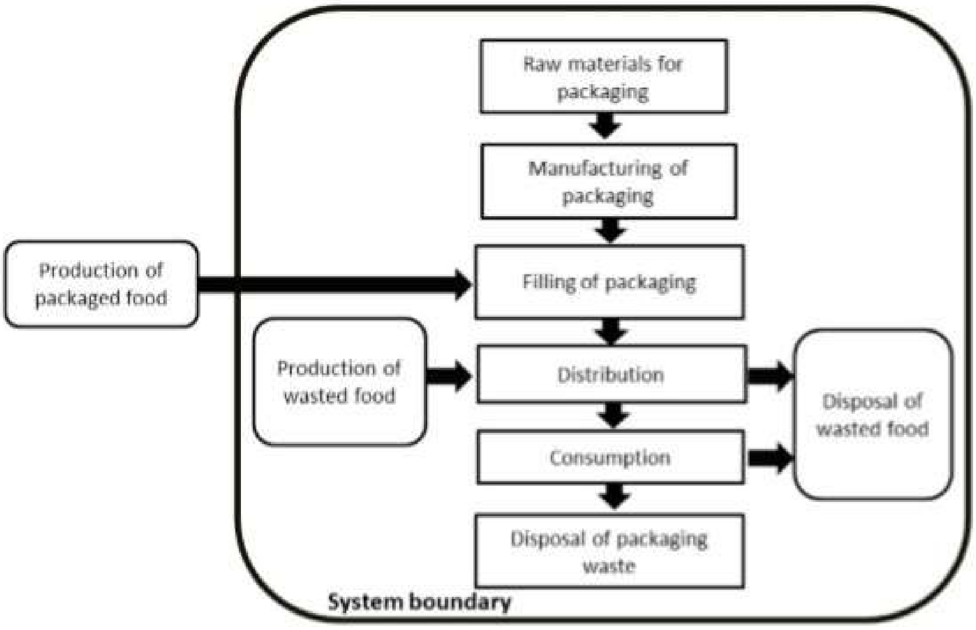

Figure 3: Integration of the product losses into packaging LCA (adopted from Grant et al, 2015)

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The amount of packaging related lost or wasted food is hard to determine. Therefore, a highly simplified, practicable approach is presented that allows the packaged product to be included in the sustainability assessment of the packaging. The Food-to-Packaging ratio (Heller at al., 2018) [24] compares the environmental impacts of the packaged food with the environmental impacts of the packaging. This indicator can be calculated for various environmental impact categories (eg. Acidification, land use, toxicity etc), however, the most reliable data is available for the climate change impact category, calculated with the GWP100 method [25]. The Food-to-Packaging (FTP) ratio calculates as follows:

$$FTP\ ratio = \frac{Environmental\ impacts\ of\ packaged\ food}{Environmental\ impacts\ of\ packaging}$$

Although the FTP ratio does not inform about the amount of food lost or wasted due to poor packaging, it puts the environmental impacts of packaging in perspective. High values indicate that product protection is paramount, while low values might indicate a potential for weight reduction.

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5 Summary of published articles

In the following, the published publications are summarised. First, those three publications are presented which are credited for the dissertation:

- Assessing the Environmental Sustainability of Food Packaging: An Extended Life Cycle Assessment including Packaging-Related Food Losses and Waste and Circularity Assessment
- Sustainability of flexible multilayer packaging: Environmental impacts and recyclability of packaging for bacon in block
- The Influence of Database Selection on Environmental Impact Results. Life Cycle Assessment of Packaging Using GaBi, Ecoinvent 3.6, and the Environmental Footprint Database

Finally, a publication is presented that fits thematically:

- Methods for the Assessment of Environmental Sustainability of Packaging: A review.

5.1 Assessing the Environmental Sustainability of Food Packaging: An Extended Life Cycle Assessment including Packaging-Related Food Losses and Waste and Circularity Assessment

This publication gives an overview of methods to assess the environmental sustainability of food packaging. Furthermore, a methodological framework for environmental assessment of food packaging is proposed.

5.1.1 Background, aim and methods

Food packaging plays a central role in our economy. Despite its important role, packaging is perceived as an environmental. Sustainable packaging must protect the packaged good as best as possible, cause as little environmental impact as possible and be as circular as possible. Although numerous methodological guides for assessing packaging sustainability exist, they often have major shortcomings. Often, relevant aspects and the important question of the calculation methodology are not sufficiently addressed.

In general, these sustainability assessment guides can be divided into three areas: Specialist literature, industry-related guides and regulatory guidance.

Specialist literature: In "Packaging for sustainability", the aforementioned principle of sustainable packaging is defined. Packaging should be effective, efficient, safe and circular. However, the work leaves open the question of which specific indicators should be calculated and with which methods [8].

Industry-related guides: These guides are aimed at companies that want or need to assess the sustainability of their packaging. The "Global Protocol of Packaging Sustainability" was published by the Consumer Goods Forum, and proposes very concrete indicators [26]. These indicators are derived from life cycle assessments, but in addition, metrics are listed to characterise circularity and packaging efficiency. Walmart requires its suppliers to complete a "Packaging Scorecard". Walmart has also developed an incentive system so that companies with particularly sustainable packaging, for example, get better placement in the shops [27].

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Regulatory: The Packaging and Packaging Waste Directive, already discussed in the introduction, refers to a number of European standards that set requirements for the energy (EN 13431) [28] and material (EN 13430) [29] recyclability, compostability (EN 13432) [23], reusability (EN 13429) [30] of packaging and Prevention by Source Reduction [31]. A number of sustainability indicators can be derived from both the directive and the standards mentioned.

The publication also describes the importance of life cycle assessment for the evaluation of packaging. In addition to the analysis of the packaging itself, the inclusion of the packaged product has increasingly come into focus in recent years. Food waste is a major social, economic and environmental problem. Some of this waste is packaging-related. Poor residual emptying, inappropriate packaging sizes as well as poor resealability can lead to product losses [32] . The environmental impact of the packaged food is usually much higher than the environmental impact of the packaging itself. Theoretically, the environmental impacts of packaging-related food waste could be attributed to the packaging, but the amount of packaging-related food losses and waste is very difficult to determine. A simple approach is to calculate the Food-to-Packaging ratio. This is done by dividing the environmental impact of the packaged food by that of the packaging [24]. Usually, the greenhouse gas potential (kg CO_2 equivalents) is used as the unit of measurement. If the value is very high, this means that the foodstuff has a significantly higher environmental impact than the packaging. In this case, packaging development should primarily focus on the best possible product protection. If the value is very low, the packaging has a relatively high environmental impact. In this case, it should be examined whether the efficiency of the packaging can be improved (e.g. weight reduction, improved recyclability).

A Circular Economy is characterised by closed material cycles and renewable energy flows. In material cycles, a distinction is made between biological and technical cycles. Accordingly, circular packaging is produced from recycled or bio-based raw materials, and is recycled, composted or ideally reused after use. It is produced using renewable energy and contains no toxic substances. The technical cycles can be described by indicators such as recycled content, technical recyclability, actual recycling rate and reusability. The biological cycles are described by the share of renewable raw materials as well as by compostability. It is important to understand that bio-based raw materials are not automatically renewable raw materials. Marine fish from overfished stocks or tropical wood from virgin forests are undoubtedly biobased resources, but by no means renewable ones. In the sense of the circular economy, the use of biobased materials is only possible if no more is extracted than can also grow back. Renewable energy flows can be described by the share of renewable energy in the total energy consumed over the life cycle of the product.

Circular is often, but by no means always, synonymous with sustainable. For example, multilayer packaging is often very resource efficient and environmentally friendly, although recycling is often not possible. Functionally equivalent recyclable solutions are sometimes much heavier and therefore cause higher environmental impacts. This conflict of goals between circularity and resource efficiency must be kept in mind.

5.1.2 Results and discussion

A holistic assessment method has to consider the three dimensions of packaging sustainability as shown in figure 4. Based on the literature described and the problems mentioned, a methodological recommendation is developed. It should follow certain core principles.

Figure 4: The three aspects of packaging sustainability

The entire life cycle should be analysed. In addition to the life cycle assessment and the circularity assessment, the role of the packaged food should also be included. In order to improve comparability and reproducibility, the calculation of the LCA should be based on the recommendations of the "Product Environmental Footprint". A selection of the three to five most important impact categories based on a normalisation and weighting of results is recommended. Table 2 provides an exemplary overview of the indicators to be evaluated.

Table 2: Overview of indicators to be evaluated

	Indicator	Method
Environmental impacts of packaging:	16 different environmental impact categories	LCA – as recommended in the PEF guidance document [19]
Consideration of packaged food	Percentage of lost or wasted food due to poor packaging	Empirical survey, Literature, Assumptions
	Food-to-Packaging ratio	Heller et al., 2018 [24]
Circularity	Recycling rate	Directive (EC) 94/62/EC (Version 2018) Article 6a,
	Recycled content	Percentage of mass %
	Recyclability	Evaluation according to three criteria: 1. existing collection system 2. sortability 3. material recyclability

5.2 Sustainability of flexible multilayer packaging: Environmental impacts and recyclability of packaging for bacon in block

This publication looks at the sustainability of different multilayer films for bacon. The packaging is assessed according to the recommendations of the previous study.

5.2.1 Background, aim and methods

Despite the relatively good shelf life of bacon [33] compared to other meat products, bacon packaging must still provide a sufficient barrier against oxygen and water [34]. Three principal types of packaging come into consideration [35]:

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- Thermoformed films: The packaging consists of two components, a forming film and a non-forming film. After the forming film is thermoformed, the product is placed in the trough. Finally, the nonforming film is placed on top and the whole is vacuumed and sealed. After use, the film is usually disposed of in the residual waste and sent to waste incineration. As the forming film is deep drawn, it must be thicker than the non-forming film. The advantage of the thermoformed two-part packaging is its consumer appeal. However, significantly more material has to be used than for the other variants since thermoforming reduces the wall thickness in some places and increases oxygen permeability

- Vacuum bag: A bag is formed from a PE/PA composite film. Sealed-edge or tubular bags are used for bacon. After placing the product in the bag, it is vacuumed and sealed in a chamber machine. During this process, flexible packaging collapses around the bacon, which creates a preservative, oxygen-deficient environment.

- Shrink bag: A bag is formed from shrinkable composite films. These films are oriented and stretched during polymer processing. The film is cooled, and the orientation is frozen in place. After reheating, polymer chains relax back into their preferred configuration, causing shrinkage. Labelling takes place before the product is placed in the shrink bag. The product is placed in the bag, shrunk and sealed under the influence of heat. During the shrinking process, oxygen also escapes.

Various materials are used for producing multilayer films:

- Polyethylene (PE) is characterised by good sealability and water vapour barrier. The inner layer of all the variants examined is made of PE.

- Polyamide (PA) gives the packaging mechanical stability. It also offers a better oxygen barrier than polyethylene.

- Ethylene vinyl alcohol (EVOH) is an excellent oxygen barrier.

Other plastics are also used. Worth mentioning are polypropylene (PP), polyethylene terephthalate (PET) and polyvinylidene chloride (PVdC).

The following table describes the six packaging variants examined:

Table 3: Examined packaging

Type	**Variant**	**Layer composition**	**Layer thickness**
Thermoformed films	1a	Thermoformed film: PE/PA/PE Cover film: PET/PE/PA/PE	Thermoformed film: 330 µm Cover film: 163 µm
	1b	Thermoformed film: PE/EVOH/PE Cover film: PP/PE/EVOH/PE	Thermoformed film: 300 µm Cover film: 200 µm
Vacuum bag	2a	PA/PE	145 µm
	2b	PA/PE	90 µm
Shrink bag	3a	PE/PVdC/PE	75 µm
	3b	PA/EVOH/PE	100 µm

Life cycle assessments were calculated for these packaging systems based on the PEF specifications. The following impact categories were evaluated: climate change, respiratory illness/fine dust, eutrophication and consumption of fossil resources. Manufacturer information on the packaging

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structure was used as the basis for the data. The ecoinvent 3.6 life cycle assessment database [36] was used.

The recyclability of the packaging was determined using the RecyClass method [37]. In addition, an assessment was carried out according to the criteria mentioned in Table 2. The food-to-packaging ratio was determined on the basis of the data provided by the manufacturers.

The food-to-packaging ratio was calculated using the values for greenhouse gas emissions.

5.2.2 Results and discussion

Figures 5, 6,7 and 8 show the results for the impact categories:

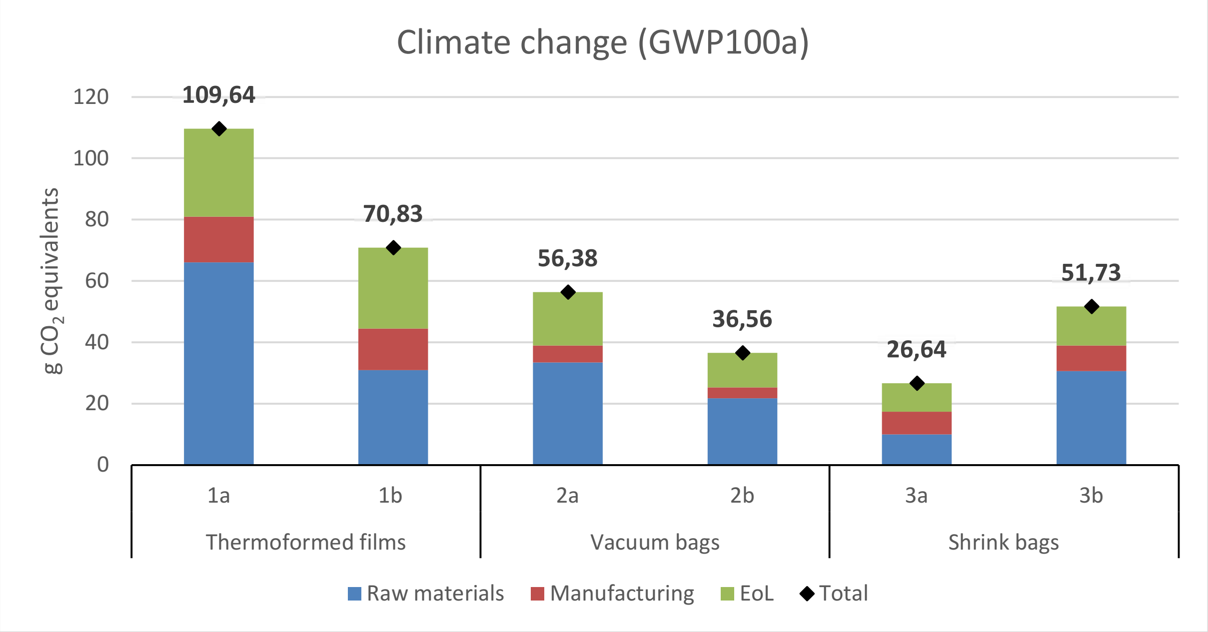

Figure 5: Results for climate change

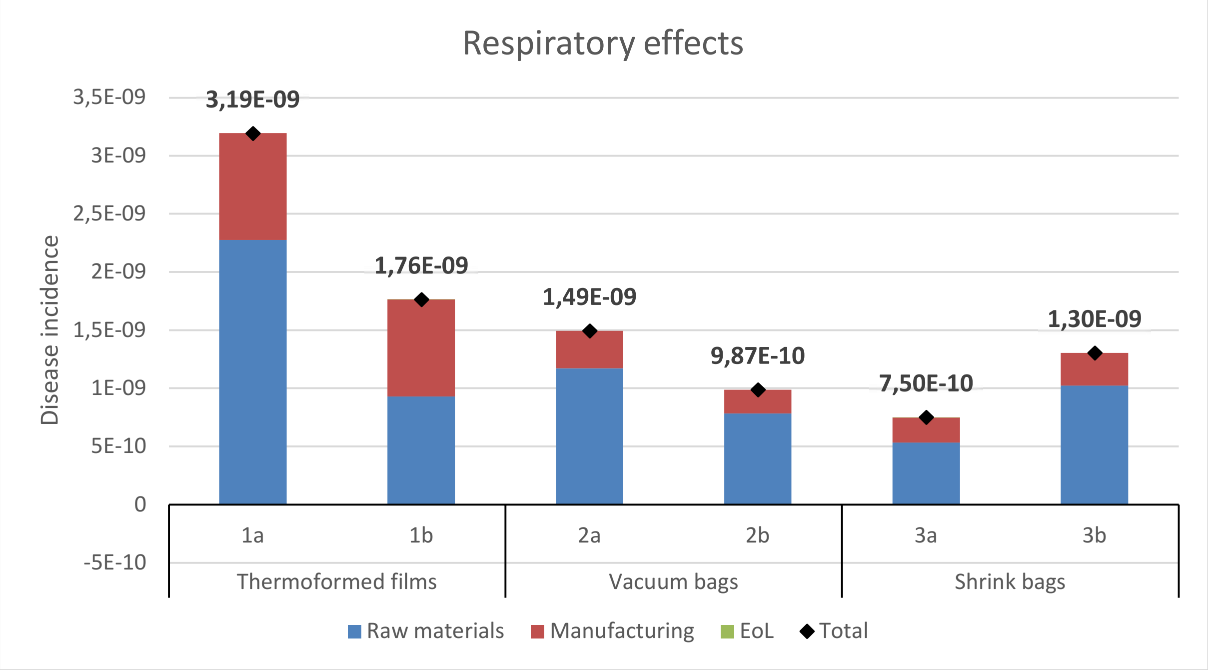

Figure 6: Results for Respiratory effects/Particulate matter

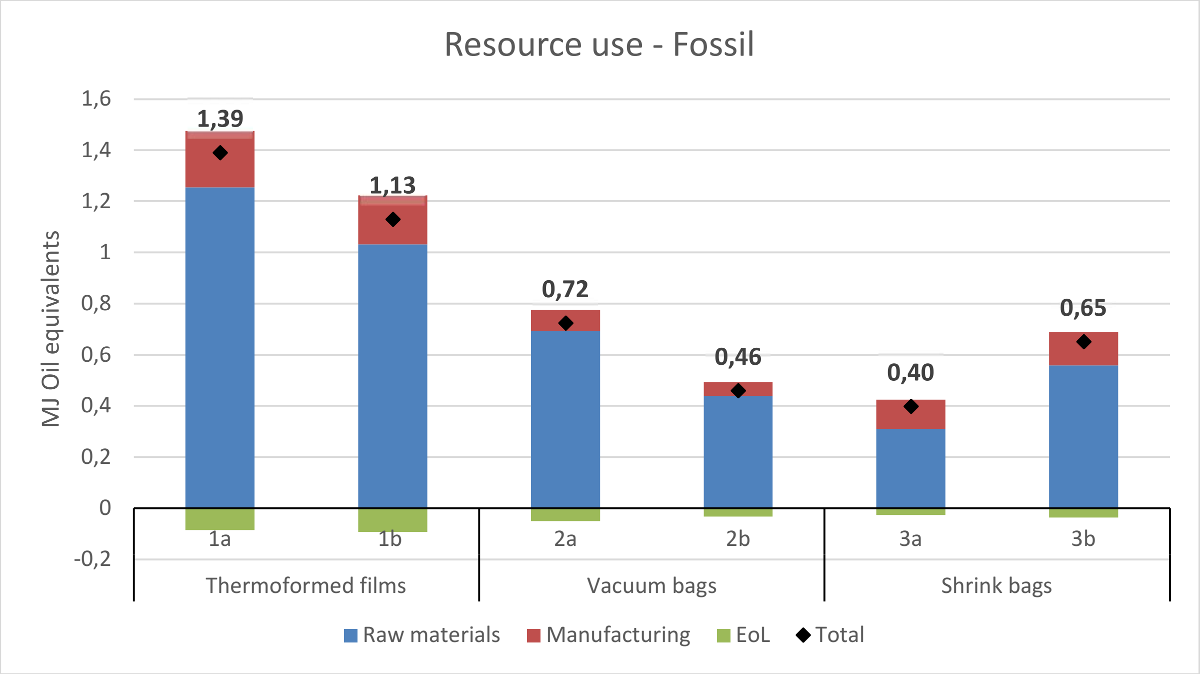

Figure 7: Results for Resource use - Fossil

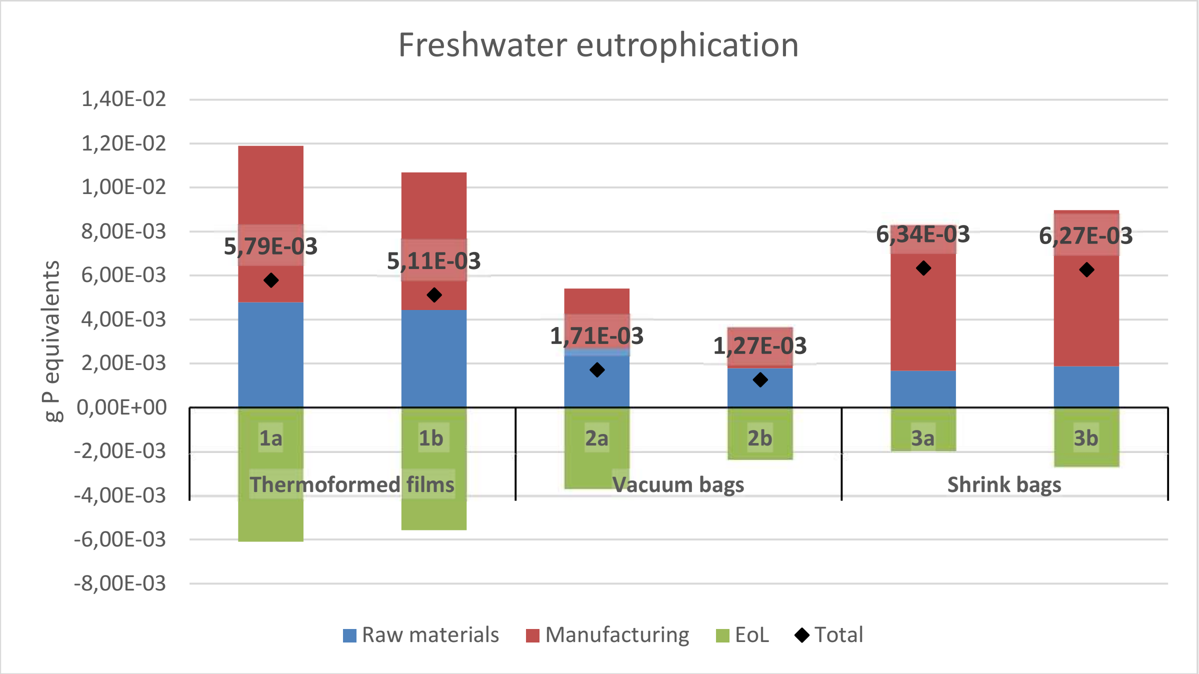

Figure 8: Results for Freshwater Eutrophication

For the thermoformed film, three different recycling scenarios were calculated. The base case 72% assumes that 100% of the films are collected and sent to recycling. The value of 72% refers to the recycling output rate, taking into account the losses during the process (see figure 9).

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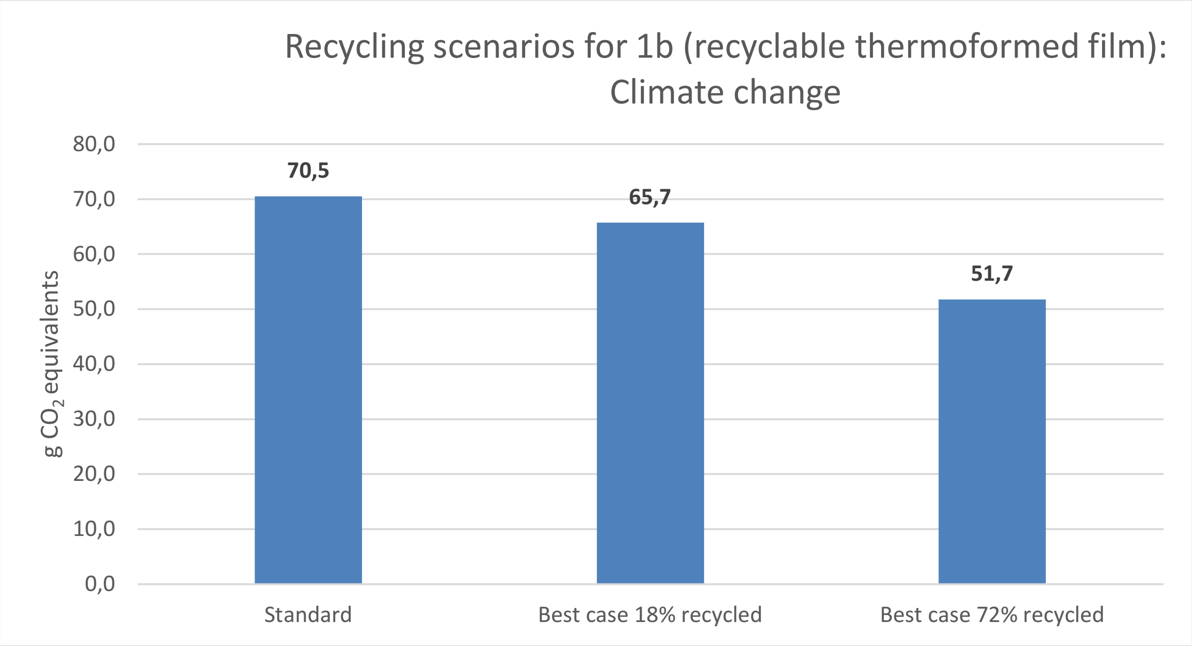

Figure 9: Recycling scenarios for variant 1b

Recyclability assessment:

Collection systems: Light plastic packaging is collected regionally. While such films are collected separately in the yellow bag in some regions, this does not apply to Vienna, for example.

Sortability: The multilayer films are smaller than A4. Therefore, they cannot be assigned to a pure material stream [38]. Sortability is poor.

Material recyclability: Since the material combinations are involved, material recycling is not possible in practice for variants 1a, 2a,2b,3a and 3b. Only variant 1b (PE with a low EVOH content) can be recycled, but with a large loss of quality.

Table 4 shows the results for the evaluation of recyclability according to the RecyClass method:

Table 4: Results of the recyclability assessment (RecyClass method)

Variant	**Result**	**Meaning**
1a	F	Not recyclable
1b	C	The package has some recyclability issues that affect the quality of its final recyclate.
2a	F	Not recyclable
2b	F	Not recyclable
3a	F	Not recyclable
3b	F	Not recyclable

Food-to-Packaging ratio:

The environmental impact (measured in greenhouse gas emissions) of the packaged meat is on average about 50 times higher than that of the packaging itself.

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Discussion:

The environmental impact of packaging depends primarily on the weight, but also on the PA content. The production of polyamide is very energy-intensive and therefore causes significantly higher emissions than the production of PE or PET.

For variant 1b (PE with low EVOH content), an optimistic scenario was calculated that assumes material recycling of the film. Even in this case, the particularly light variants 2b and 3a perform better (see figures 5 and 9).

The results of this study show that there is a clear hierarchy of necessities in the development of meat packaging. Optimal product protection must come first (very high FTP value). If this protection is guaranteed, then resource efficiency (weight reduction, energy savings in production) brings greater benefits than optimised recyclability. There is a clear conflict of objectives here, as there is regulatory pressure to make packaging recyclable. Under the current framework conditions, the question arises as to whether recyclable meat packaging makes sense. On the other hand, it is quite conceivable that improved materials and recycling systems will make it possible to recycle such films in an ecologically and economically reasonable way in the future.

5.3 The Influence of Database Selection on Environmental Impact Results. Life Cycle Assessment of Packaging Using GaBi, Ecoinvent 3.6, and the Environmental Footprint Database

This publication explores the question of how the choice of LCA database influences the results for different packaging systems.

5.3.1 Background, aim and methods

The results of life cycle assessments can influence important decisions. Therefore, the question arises how reliable the results are. It is well known that assumptions and methodological approach have a strong influence. But also the choice of database [39 -41] and even software [42] has a significant influence. Since in this study different databases as well as different software were used, the term software-database combination is used.

Six different representative packaging systems covering all major packaging materials were analysed. These are:

- PET bottle
- Plastic bag (PE)
- Glass bottle (single use)
- Aluminium can
- Tinplated steel can
- Corrugated box

Life cycle assessments were carried out for this packaging in accordance with the PEF recommendations. This means that the same impact assessment method was always used. The calculations were carried out using the software-database combinations shown in table 5.

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Table 5: Overview of the examined software-database combinations

Database	**Software**
GaBi [43]	GaBi
ecoinvent 3.6 (cut off) [36]	openLCA
EF database for openLCA (EF DB) [44]	openLCA

The aim was to carry out the calculations according to the same methodology. The "Circular Footprint Formula" recommended by PEF was used as the allocation method. However, it turned out that this was not always possible, as some data sets (e.g. glass data set in GaBi, sheet metal in ecoinvent) were already modelled according to a different allocation method. Therefore, for consistency reasons, a different allocation method had to be applied to these systems.

The results for the 16 PEF impact categories were normalised and weighted to identify the most relevant impact categories. For these categories, an in-depth analysis was made of where the deviations come from. Furthermore, it was systematically checked whether the impact assessment methods were implemented correctly.

5.3.2 Results and discussion

The following graphs show the results of the calculations of the most relevant environmental impact categories. The percentage deviations are shown. The results from the GaBi database were defined as 100%.

The results for the PET bottle are shown in figure 10.

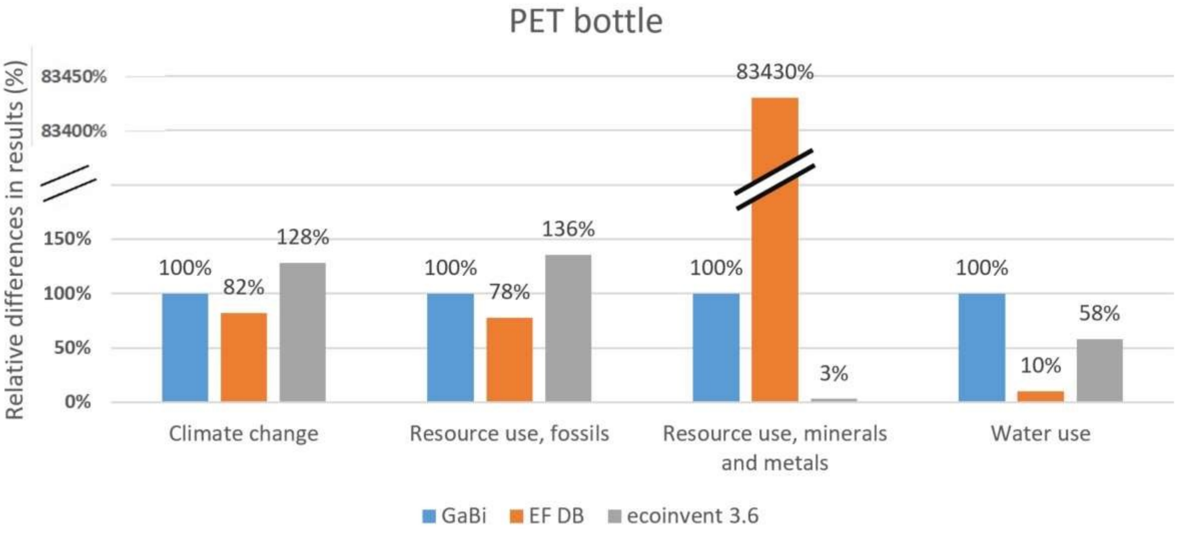

Figure 10: Results for the PET bottle

What is particularly striking here is the large difference in the category "Resource use, minerals and metals". The EF database assumes a significantly higher antimony content in the PET granulate than GaBi. The low value for ecoinvent is due to the incorrect implementation of the impact assessment method for ecoinvent.

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Figure 11 shows the results for the PE plastic bag.

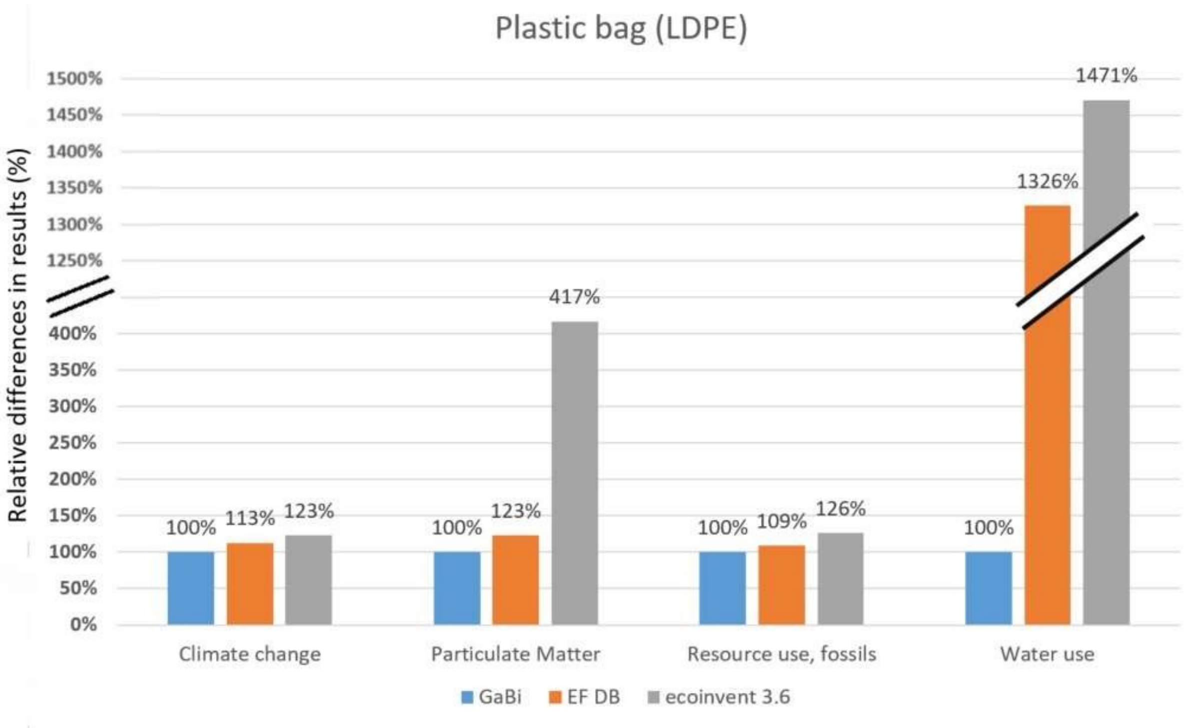

Figure 11: Results for the plastic bag

The significantly higher values for "Particulate matter" in ecoinvent come from much higher SO2 and PM2.5 emissions from ethylene production by steam cracking. The anomalously low value for water consumption in the GaBi database is striking. For polyethylene production there is an implausible negative value for water consumption.

Figure 12 shows the results for the glass bottle.

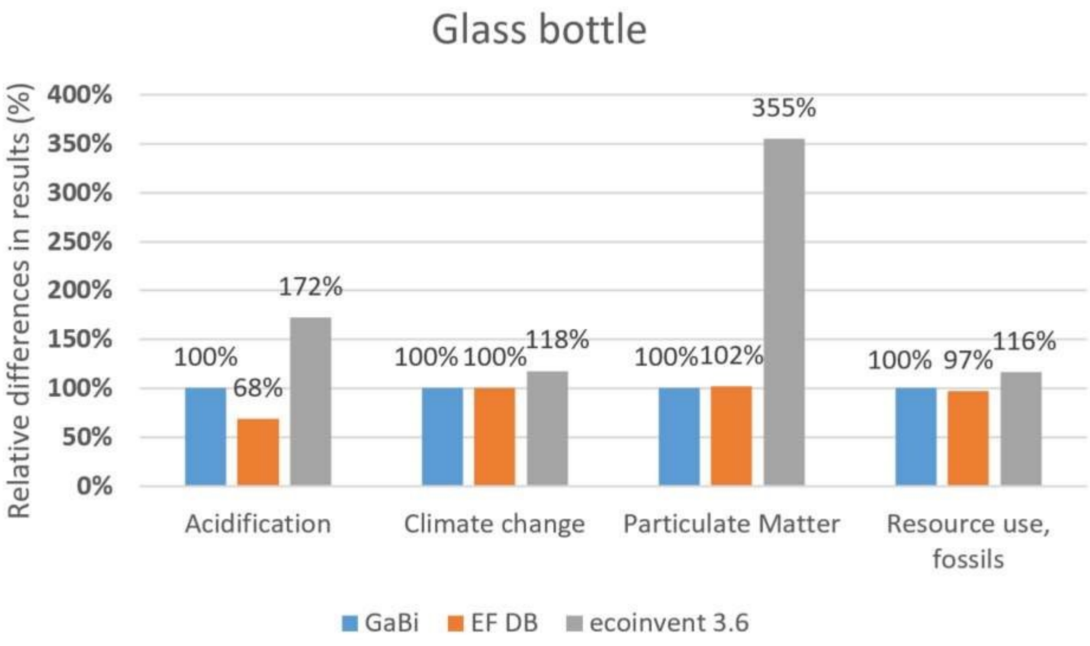

Figure 12: Results for the glass bottle

Significantly higher SO2 and particulate matter emissions in the ecoinvent data set for glass production lead to strikingly high values in the acidification and particulate matter categories.

Figure 13 shows the results for the aluminium can.

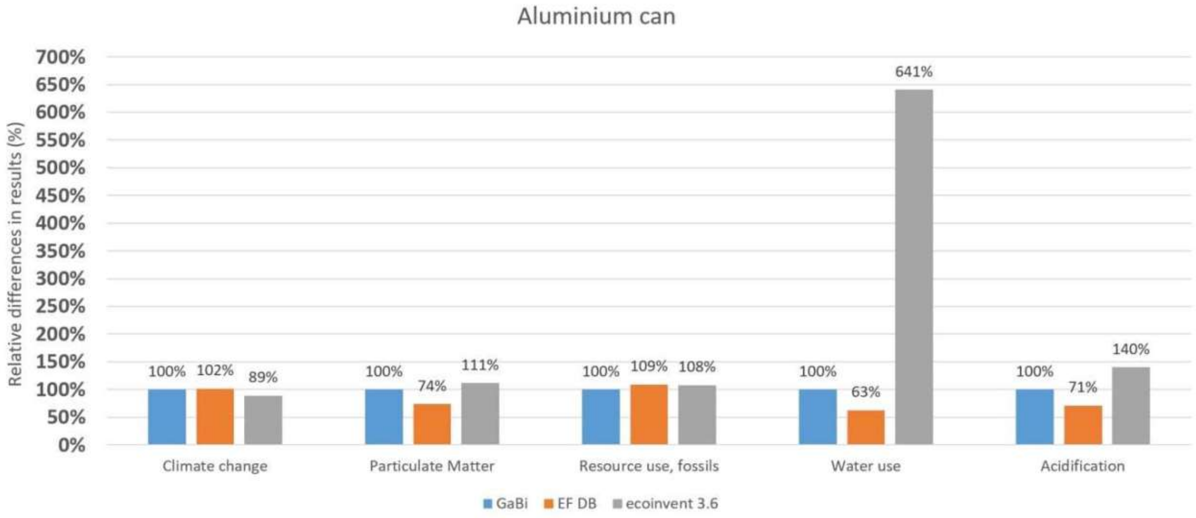

Figure 13: Results for the aluminium can

The high values for water consumption are due to the poor implementation of the impact assessment method for ecoinvent. The principle of this method (AWARE - Available WAter REmaining) is based on regionalisation [45]. It is not just about the absolute water consumption in m³, but about how this water consumption affects the problem of water scarcity. The consumption of 1 litre of water has a different (smaller) impact in Norway than in Saudi Arabia. Therefore, there are regionalised CFs (characterisation factors) for water from different regions. For ecoinvent this regionalisation is not implemented, a high global average value is always used (CF = 42.85). However, a significant part of aluminium production takes place in water-rich countries such as Norway (CF= 0.63). In GaBi and the EF database, this low characterisation factor is also correctly taken into account.

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Figure 14 shows the results for the tin can.

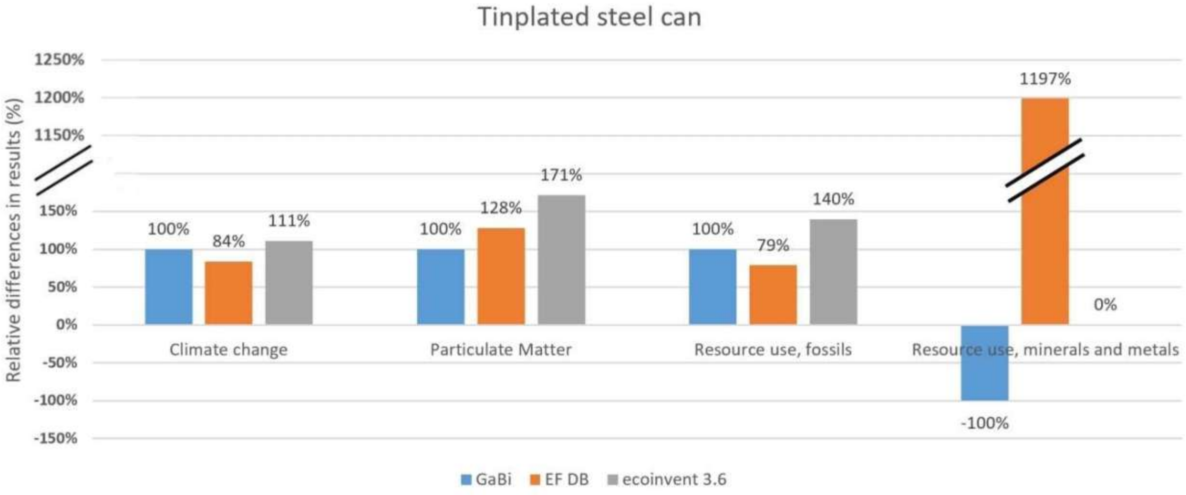

Figure 14: Results for tinplated steel can

For the category "Particulate matter" ecoinvent assumes very high particulate matter emissions from coal production. The negative values for "Resource use, minerals and metals" in GaBi come from the data set used for the calculation of the credit. The high values in the EF database are caused by copper consumption.

Figure 15 shows the results for the corrugated cardboard box.

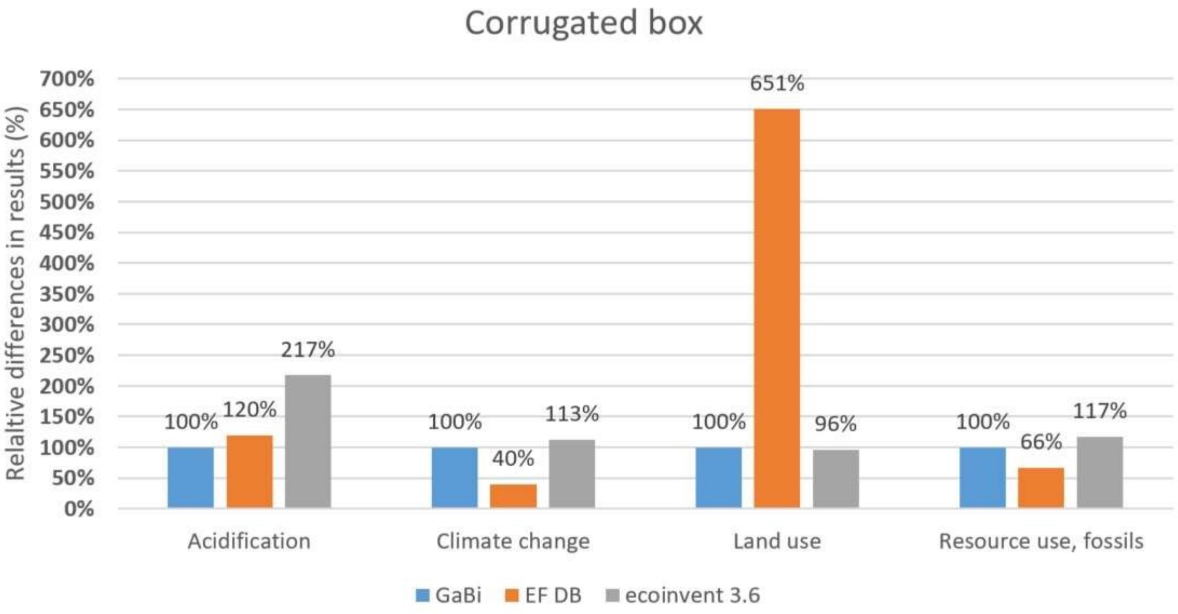

Figure 15: Results for corrugated box

The unusually low values for "Climate change" in the EF database are due to negative methane emissions. This is obviously a mistake, because the corrugated board data set in all three databases refers to the same study. If the negative sign were changed, the value would roughly correspond to the values of GaBi and ecoinvent. For land use, the EF database assumes much higher values for the flow "forest, used".

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Since electricity always has a relevant influence on the overall result, a comparative evaluation was also carried out for the European electricity mix (see figure 16).

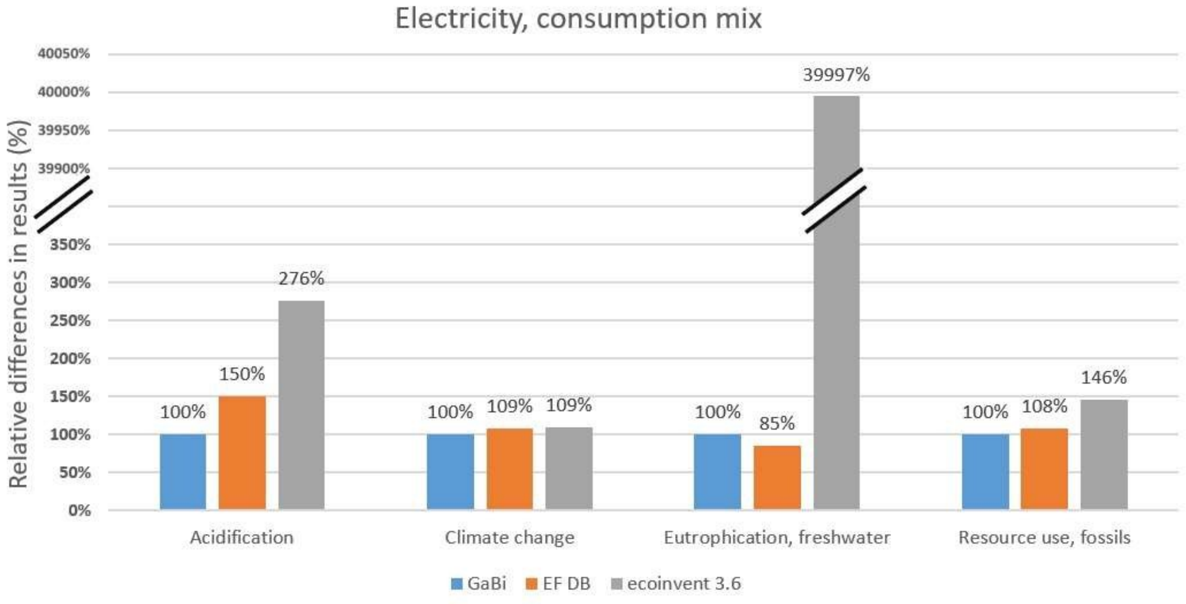

Figure 16: Results for the European electricity mix

According to ecoinvent, the high values for acidification are due to significantly higher SO_2 emissions from coal-fired power plants. Coal also plays a role in freshwater eutrophication. According to ecoinvent, the overburden from coal mining releases phosphates into the groundwater. These phosphate emissions are completely missing in the other databases.

Differences in the implementation of the impact assessment methodology:

The methods published by the European Commission consist of an Excel list of characterisation factors for different impact categories [46]. These original factors were compared with the characterisation factors as implemented for the different software database combinations. A clear difference can be seen in the regionalisation. There are regionalised factors for acidification, land use, terrestrial eutrophication and water use. While for global warming it is irrelevant where the emissions come from, for water, for example, it is very relevant where the water is consumed. For acidification, for example, the Czech Republic has a much higher characterisation factor for SO_2 than most other countries.

In ecoinvent there are no regionalisations for any impact category, in the EF database only for water consumption. GaBi provides regionalisation for land use and water depletion. Regionalisation for acidification and terrestrial eutrophication has not been implemented anywhere. These differences partly explain differences in the overall results.

Smaller differences could also be found in the characterisation factors. For example, the factor for methane in ecoinvent is 36.75, while in the original it is 36.8. For the category "Resource use, minerals and metals", several characterisation factors are missing in ecoinvent. However, this error has been corrected in the meantime (as of the end of 2020).

This study shows that the choice of database has a major impact on the results. While the results for climate change mostly agree relatively well, this is not the case for other impact categories. The GWP100 (Global warming potential - 100 years) method is a very robust method and the data basis for greenhouse gas emissions is comparatively solid. Other impact assessment methods are less robust. In particular, the methods for land use and water scarcity are still poorly implemented. The method "Resource use, minerals and metals" is particularly problematic. The values for the PET bottle and the tinplate can seem completely random and are not even comparable in terms of orders of magnitude. Besides the weakness of the method, there is also the question of whether the scarcity of resources is an ecological problem at all [47].

It is noticeable that the results of the impact assessments from ecoinvent 3.6 are commonly higher than GaBi results. A comparison of transport processes also shows higher results for ecoinvent in the category climate change. The documentation of the datasets clearly shows that ecoinvent also includes road maintenance and vehicle wear, which is not the case with GaBi. Different system boundaries lead to higher results. In many cases, the ecoinvent datasets contain considerably more background processes (e.g., wear and tear of infrastructure, maintenance work, etc.) than GaBi.

Different allocation methods also strongly influence the result [48]. The choice of allocation method influences both the handling of the recycled content of a product and the recycling at the end of the life cycle. The sheet metal datasets of the three databases all contain a certain amount of secondary raw materials. In GaBi the data set was calculated according to the worldsteel method [49], in ecoinvent according to the cut-off method and in the EF database according to the "Circular Footprint Formula". Consequently, the entire life cycle had to be calculated according to the given method.

The quality of the data sets also plays a significant role. Many of the differences can be attributed to different methodological approaches (system boundaries, allocation methods, etc.). However, there are also several obvious errors that can distort the results.

The database developers are very aware of these problems and are constantly working on improving their databases. However, due to the constantly growing amount of data, this process can never be completed. LCA practitioners must be able to judge the quality of the data used.

5.4 Methods for the Assessment of Environmental Sustainability of Packaging: A review.

This review gives an overview of user-friendly LCA tools for packaging.

5.4.1 Background, aim and methods

There is a great demand for life cycle assessments for packaging. However, carrying out a complete, ISO 14040/44-compliant life cycle assessment involves a great deal of effort and expense. Many companies also want to be able to carry out assessments for their packaging themselves without major effort. The author has tested the programmes mentioned in table 6.

Against this background, a market for so-called "S-LCA tools" has emerged. S-LCA stands for "Simplified/Streamlined Life Cycle Assessment". These are online programmes that can be operated via a web browser. There are various programmes, all of which essentially function in the same way. The user logs in and can create a project. A package is now modelled in this project. To do this, the components that make up the packaging must be specified. For a PET bottle, for example, the components would be bottle, label and cap. The user must now define the weight, materials and manufacturing processes of the individual components in more detail. To do this, predefined variants can be selected from drop-down lists. Then secondary and tertiary packaging can also be specified. Often, the region of manufacture can also be specified and various disposal scenarios, for which the desired recycling rate can be specified in a field. There is usually an automatically generated pdf report

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containing the results for predefined impact categories. All programmes allow to compare different scenarios. An intelligent employee can learn to use such a programme in one day. These online tools are a compromise: Ease of use and speed come at the expense of flexibility and accuracy. There is usually an annual fee of several thousand euros per year to use them.

5.4.2 Results and discussion

The author has tested the programmes mentioned in table 6 himself. Since this study was prepared at the beginning of 2017 and the framework was written at the end of 2020, no claim to completeness is made here, as new providers are constantly entering the market.

Table 6: S-LCA tools for packaging

S-LCA tool	Provider	Comment
Packaging Impact Quick Evaluation Tool (PIQET) [50]	Life Cycle Strategies Pty Ltd	One of the pioneers in the field. Meanwhile also offers the calculation of the Material Circularity Indicator
GaBi Packaging Calculator [51]	Sphera	Also offers the possibility of a recyclability assessment
Bilan Environnemental des Emballages (BEE) [52]	Eco-Emballages/CITEO	Best free programme, but only applies to France.
PackageSmart [53]	EarthShift Global LLC	
COMPASS – Comparative Packaging Assessment [54]	GreenBlue	The use of COMPASS is recommended by the influential Sustainable Packaging Coalition. Members of this organisation include companies such as Walmart, Amazon and P&G.
EcodEX [55]	Selerant	EcodEX covers not only packaging, but also food.

In general, most providers now also offer circularity indicators. While this was not yet the case at the time of publication (June 2017), most providers now offer a circularity assessment. Here, the GaBi Packaging Calculator stands out positively, as it offers a meaningful assessment of recyclability.

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6 Conclusion and scientific contribution

6. 1 Conclusion

In summary, a holistic sustainability assessment of packaging must cover the following three aspects:

- Environmental impacts of packaging
- Circularity
- Environmental impacts of packaged food

6.1.1 Environmental impacts of packaging

For this purpose, an LCA has to be carried out. The use of the PEF method is recommended, as European standardisation would improve the reproducibility and comparability of the results. In addition, the allocation method recommended by the European Commission ("Circular Footprint Formula") is advantageous over other allocation methods because it takes into account both the use of recycled material and recycling at the end of the product's life. It also takes into account the important aspect of quality losses during recycling. Numerous calculations were carried out as part of this work. In the process, certain environmental impact categories have repeatedly emerged as particularly relevant and meaningful for all packaging types. These are:

- Climate change
- Acidification
- Respiratory effects/PM
- Water scarcity

For biogenic materials, the category "land use" is also recommended. The use of aggregated indicators is strongly discouraged.

In any case, the user needs a solid understanding of the impact assessment methods. While some of these methods are very robust, there are great uncertainties with other methods or they are often still very poorly implemented in the LCA databases. Furthermore, the user must be able to assess the quality of the data sets used.

6.1.2 Circularity

The key indicators used should be relevant for the packaging. When specifying a bio-based content, it must be noted that a bio-based material can only be described as renewable if it can be proven to originate from sustainable cultivation.

The indication of the recycled content is becoming a regulatory necessity for some packaging, as the EU Single Use plastics Directive will require a minimum recycled content for PET bottles in the future.

When stating a recycling quote, Article 6a of Directive on Packaging and Packaging Waste [10] must be followed: Only the material that is actually recycled after collection and sorting is to be included. The collection rate cannot therefore be stated as a recycling rate.

When assessing recyclability, these three aspects must always be evaluated:

- Collection system
- Sortability
- Material recovery

The use of an aggregated indicator, such as the Material Circularity Indicator, is also explicitly not recommended here, as the informative value is low.

6.1.3 Consideration of the packaged food

Packaging-related food waste is a relevant parameter in the sustainability assessment of packaging. However, it can only be collected empirically, if at all. Therefore, the collection of this important variable is almost impossible within the framework of most studies.

A highly simplified, but nevertheless very meaningful value is the food-to-packaging ratio. The inclusion of the environmental impact of the entire packaged food puts packaging in perspective. The use of this ratio is recommended.

6.2 Scientific Contribution

This dissertation deepens the knowledge of what environmental sustainability means in relation to packaging. The most important aspects of packaging sustainability are identified and the calculation of the relevant indicators is described. This fills the gap mentioned in the problem statement. There is a lot of literature that describes in general terms what packaging sustainability is. There are also a large number of publications that deal with calculation methods in detail. This paper combines these two perspectives, the bird's eye view and the detailed perspective. The most important aspects of packaging sustainability are mentioned, namely environmental impact of the packaging, interaction with the packaged product and circularity. At the same time, concrete, meaningful indicators characterising these aspects are also described. Since the calculation methodology and the choice of data used have a very decisive influence on the results, these aspects are also dealt with in detail.

Another important contribution is that important conflicting goals are highlighted. As much as the goals of the European Circular Economy Package are to be welcomed, it should not be overlooked that recyclability does not always lead to resource efficiency.

This dissertation not only makes an important scientific contribution, it is also of great relevance for practice. On the part of industry, there is great interest in assessment methods for packaging. While the classic life cycle assessment is a generally known and established tool, there is a great need for development in circularity assessment and in the integration of the packaged food into the sustainability assessment. The findings of this work also flow into the author's daily professional practice.

It is clear that such work is always part of a larger development. During the last few years, a number of researchers and also sustainability experts from the business community have been working very intensively on the development of these assessment methods. The development of a holistic assessment method that covers different aspects, while providing meaningful and reproducible results, is a concern for many people.

Furthermore, it is clear that such work can only ever be a snapshot. There are constantly new findings and developments. While in the past the focus was on resource scarcity, acid rain and ozone depletion, today climate change and plastic waste dominate the sustainability discourse. Which issues will be in

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the focus in ten years is open. Accordingly, a method for assessing the sustainability of packaging must be constantly developed further. The present work should also serve as a basis for future developments.

When dealing with such a question, it must be recognised that this topic can never be completely concluded. On the one hand, the packaging systems to be evaluated change, on the other hand, the environmental situation also changes. Ultimately, the choice of indicators is always dependent to a certain extent on subjective values. The development of an assessment methodology always depends on changing political and social conditions.

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8 Full text: Paper 1

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Assessing the Environmental Sustainability of Food Packaging: An Extended Life Cycle Assessment including Packaging-Related Food Losses and Waste and Circularity Assessment

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Abstract: Food packaging helps to protect food from being lost or wasted, nevertheless it is perceived as an environmental problem. The present study gives an overview of methods to assess the environmental sustainability of food packaging. Furthermore, we propose a methodological framework for environmental assessment of food packaging. There is a broad consensus on the definition of sustainable packaging, which has to be effective, efficient, and safe for human health and the environment. Existing frameworks only provide general guidance on how to quantify the environmental sustainability of packaging. Our proposed framework defines three sustainability aspects of food packaging, namely direct environmental effects of packaging, packaging-related food losses and waste, as well as circularity. It provides a list of key environmental performance indicators and recommends certain calculation procedures for each indicator. The framework is oriented towards the Product Environmental Footprint initiative and the Circular Economy Package of the European Union. Further research should develop a method to determine the amount of packaging-related food losses and waste. Moreover, future studies should examine the potential environmental benefits of different measures to make food packaging more circular.

Keywords: food packaging; environmental sustainability; life cycle assessment; circular economy; food losses and waste; sustainability framework

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1. Introduction

Food packaging fulfills many essential functions. It protects food from detrimental physical, chemical, and biological influences. The containment function enables distribution and prevents product losses through spillage, friction of loose materials, and mixing of different products. Packaging adds convenience to food and facilitates accessibility and easy preparation. As a communication medium, it informs the consumer about a product's content, shelf life, and storage conditions [1]. Food packaging also contributes to sustainability, since it prevents food waste and allows for an efficient distribution of the products [2–4]. Notwithstanding the aforementioned benefits, food packaging is increasingly required to become more sustainable, since the production, use, and disposal of a packaging are associated with a multitude of environmental impacts [4,5], hence referred to as direct effects.

In addition to the direct effects, there are also adverse environmental effects indirectly caused by inadequate packaging, such as packaging-related food losses and waste (FLW). Per definition, food losses occur during production and processing, while food waste refers to the losses at the end of

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the supply chain, namely during retail and end-consumption [6]. The reasons for FLW are manifold and to a certain extent related to packaging [7]. For example, food degrades if the packaging does not provide proper protection against oxygen, moisture, and microbes. Packaging failures can cause damage during transportation. Packaging that is not easy to empty or portion sizes which are too large may lead to FLW at the end-consumer stage [2]. Recent research shows that the environmental burden of FLW often exceeds that of packaging [8–11].

Moreover, food leftovers can negatively affect the recyclability of packaging [12,13]. Recyclability is an important property of circular packaging. The concept of circularity in the context of sustainable production describes the restorative and preservative character of a product. In contrast to a linear product, a circular product contains renewable or recycled content or reused parts and is compostable, recyclable, or reusable, and was produced using renewable energy [14,15].

As part of its effort to transform Europe's economy into a more sustainable one, the European Union adopted a new set of measures, commonly referred to as the Circular Economy Package. These measures include several legislative proposals on waste, which aim to increase recycling rates, boosting the uptake of secondary material by industry, reducing food waste and promoting nontoxic life cycles [16]. The amended Directive on Packaging and Packaging Waste [17] will have far-reaching consequences for the packaging supply chain, because higher recycling rates require a redesign of packaging and massive investment in recycling infrastructure. The European Council approved the amendments in 2018 [18]. Moreover, leading brands, retailers, and packaging companies committed themselves to the goals of the circular economy and working towards 100% reusable, recyclable, or compostable packaging by 2025 or earlier [19].

The waste hierarchy, as defined in article 4 of Directive 2008/98/EC on waste, ranks the different end-of-life alternatives and clearly explicates which options (a. prevention, b. preparing for reuse, c. recycling, d. other recovery, and e. disposal) are preferable from an environmental point of view [20]. Although the waste hierarchy is in most cases supported by life cycle assessment (LCA) [21,22], there are notable exceptions [23]. Replacing nonrecyclable, lightweight flexible packaging with alternative, easy-to-recycle packaging materials may lead to adverse environmental effects [24–27]. It is, however, important to note that circularity is rather a political and legal requirement for packaging producers and not per se environmentally preferable.

Taken together, the abovementioned findings suggest that it is necessary to take the following environmental aspects into account, when assessing the environmental sustainability of packaging.

- Direct environmental impacts caused by the production and disposal of packaging.
- Indirect environmental impacts caused by, e.g., packaging-related FLW.
- Circularity of packaging.

The basis for improvement in these fields is measuring direct and indirect effects in addition to the circularity of packaging in a comprehensible way. Hence, quantification of the environmental performance of packaging is a prerequisite for management of the environmental impacts of packaging.

Against this background, the present study on the one hand aims to identify the most relevant Key Environmental Performance Indicators (KEPIs) for food packaging. These KEPIs should cover the most relevant aspects of environmental sustainability, without disguising potential conflicts of interests and tradeoffs between different aspects. Moreover, they should support decision-making at the product level. Equally important is the question, which methods are best suitable for calculating these KEPIs. On the other hand, the study aims to set up a methodological framework for a holistic environmental assessment of food packaging. The focus of this work is on the environmental aspects of packaging hence the aspect of human health is not considered.

The point of departure for this paper is the underlying hypothesis that existing frameworks and methodologies need further refinement, because either they ignore important aspects or they are so unspecific, that they do not give guidance on how to calculate the relevant indicators in a scientifically substantiated and comparable manner.

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2. State-Of-The-Art

This section discusses the state-of-the-art of existing approaches for the assessment of the environmental sustainability of food packaging. It gives an overview of existing sustainability frameworks, followed by a brief description of packaging LCAs, packaging-related FLW, and circularity. It concludes by highlighting possible conflicts of interests and trade-offs between the various sustainability aspects of packaging.

2.1. Existing Methodological Frameworks for Packaging Sustainability

While a methodology is a system of methods and principles for action, a framework is a system of rules, ideas, or beliefs that is used in planning and decision-making. Based on this, a methodological framework is defined as a specific arrangement of guiding principles and methods supporting a basic idea [28]. An important distinction can be made between methodological frameworks, which exclusively give guidance on how to assess packaging sustainability and those that explain how to improve packaging sustainability. In a broader sense, environmental legislation can also be understood as a methodological framework, for the reason that it defines legally binding targets, which are based on guiding principles. These legal frameworks often imply the use of certain methods. The relevant frameworks can be categorized according to their origin:

- Specialist literature
- Business (including guidance documents from industry associations or retailers)
- Policy (including legislation and Extended Producer Responsibility Schemes)

The reviewed frameworks were investigated under the following aspects.

- What is the focus of the framework?
- How is the environmental sustainability of packaging defined?
- Which environmental indicators are proposed?
- Is it explained, how these indicators have to be calculated?

Aspects of economic and social sustainability, which are to a certain extent covered by the reviewed frameworks, are excluded from this analysis. The presented frameworks have been selected for their influence, their quality and their relevance in the European context.

2.1.1. Specialist literature

The framework proposed by Verghese et al. [29] in “Packaging for Sustainability“ is based on the idea that businesses must address sustainability and have to include sustainability into the corporate strategy. The authors outline the outstanding relevance of packaging and the necessity to include packaging in the corporate sustainability strategy. They define sustainable packaging as safe, efficient, effective, and cyclic. These frameworks introduce several assessment methods in very general terms without explaining calculation procedures in detail.

2.1.2. Business

The Global Protocol of Packaging Sustainability 2.0 aims to set up a common language to describe the sustainability framework and the measurement system. It shall serve as a kind of “dictionary for packaging sustainability“. The target audience is the Fast Moving Consumer Goods sector. It mainly focuses on the description of packaging attributes and environmental indicators; however, economic and social indicators are included as well. Attributes refer to characteristics such as recyclability, while environmental indicators refer to impacts on the environment, e.g., global warming. Guiding principles for sustainable packaging are not given. It focuses on the quantitative assessment of packaging sustainability [30].

The Sustainable Packaging Coalition (SPC) is an industry association based in the United States. Membership is voluntary. The objective of the coalition is "to collectively strengthen and advance the business case for more sustainable packaging". The SPC provides tools and resources to their members to make packaging more sustainable. Sustainable packaging is defined as being beneficial for individuals, cost-efficient, recoverable, nontoxic, and manufactured using renewable energies [31].

Walmart claims to pursue the goal of reducing environmental impacts of marketed products. Suppliers are required to provide relevant information concerning the sustainability performance of their products to Walmart. Based on this information a sustainability score is calculated. Walmart issued a Sustainable Packaging Playbook (SPP) to inform suppliers on how to improve their Sustainability Index Score by improving packaging. The requirements for sustainable packaging are similar to the other mentioned frameworks; however, it is noteworthy that Walmart emphasizes the importance of end-consumer communication of proper disposal. The SPP recommends the use of LCA to assess water use, greenhouse gas emissions, and material health. It provides guidance on how to improve the recyclability of packaging and recommends the use of the How2Recycle® label to inform customers about the recyclability; moreover, it is relatively specific about the methods applied [32].

2.1.3. Policy

The Sustainable Packaging Guidelines (SPG) have to be implemented by all companies signed to the Australian Packaging Covenant Organization, which is part of an obligatory product stewardship program regulated by the National Environment Protection (Used Packaging Materials) Measure 2011 [33]. Signatories are brand owners in the packaging supply chain. According to the SPG, sustainable packaging is fit-for-purpose, resource-efficient, made from low-impact materials, and reusable or recyclable at the end of its useful life. Twelve different design strategies are derived from these four overarching principles. Signatories have to document their packaging's compliance with the design strategies by filling out a questionnaire and providing documentary evidence for their statement. Although Extended Producer Responsibility Schemes exist in many countries, the Australian system is remarkable for its holistic definition of packaging sustainability and the fact that it provides a method to check the compliance with the packaging sustainability principles [34].

The amended Directive 94/62/EC on Packaging and Packaging Waste [17] aims to prevent the production of packaging waste and increase the reuse and recycling of packaging in order to contribute to the transition towards a circular economy. The directive prescribes mandatory recycling rates for different packaging materials (Article 6). EU member states are responsible for attaining the ambitious targets. They are obliged to establish Extended Producer Responsibility Schemes for packaging, which implies that producers are responsible for attaining the higher recycling rates using recyclable packaging. The directive prescribes maximum concentration levels of lead, cadmium, mercury and hexavalent chromium present in packaging (Article 11). Annex II describes requirements for packaging, comprising recoverability, and weight reduction. Article 10 refers to a series of European standards defining requirements for recyclability [35], compostability [36], source reduction [37], energy recovery [38], and reuse [39].

The other relevant directive amended in 2018 is the Directive 2008/98/EC on Waste [20], which "lays down measures to protect the environment and human health by preventing or reducing the generation of waste, the adverse impacts of the generation and management of waste and by reducing overall impacts of resource use." It defines a waste hierarchy with far-reaching consequences for packaging design, although specific waste streams may depart from the waste hierarchy if justified by life cycle thinking (Article 4). This implies the use of LCA.

2.1.4. Summary

The majority of the reviewed frameworks are very similar in their definition of packaging sustainability. Sustainable packaging must be effective in fulfilling its core functions, primarily protection of the packaged good, efficient in using not more resources than necessary, safe for

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the environment and for human health, and circular. Most of these frameworks stay very vague regarding calculation of indicators. Only the Global Protocol on Packaging Sustainability [30] gives an exhaustive list of indicators to quantify the contribution of the packaging to the aforementioned sustainability dimensions, but it does not explain calculation procedures in sufficient detail to allow for reproducibility and comparability of results. Table 1 gives a systematic overview.

Table 1. Overview of reviewed frameworks for packaging sustainability.

Framework	Focus	Principles	Indicators
Packaging for sustainability [29]	Design for sustainability	Sustainable packaging is: • Effective • Efficient • Cyclic • Safe	General reference to LCA
Global Protocol of Packaging Sustainability 2.0 [30]	Assessment of packaging sustainability	No explicit definition	• Detailed list of indicators • Description for each indicator • Reference to LCA • Reference to EN 13430
Sustainable Packaging Coalition [31]	Improvement of packaging sustainability by voluntary commitment of members	Sustainable packaging is: • sourced responsibly • effective and safe • meets market criteria • made using renewable energy • recycled efficiently	• No preset indicators • Reference to the LCA Tool COMPASS
Walmart "Sustainable Packaging Playbook" [32]	Sustainability requirements for suppliers	Design Priorities: • Optimize Design • Source Sustainably • Support Recycling	• Sustainability Index • Preset questionnaire
Sustainable Packaging Guidelines [34]	Extended Producer Responsibility	Sustainability principles: • Fit-for-purpose • Resource efficiency • Low-impact materials • Resource recovery	• Consideration of compliance with principles • Preset questionnaire
Directive 94/62/EC [17]	Legal measures	Packaging requirements: • Weight and volume reduction • Design for recovery • Minimized use of hazardous substances	• Rules for calculating recycling rates • Reference to standards for recoverability and source reduction • Concentration levels of heavy metals
Directive 2008/98/EC [20]	Legal measures	Disposal of packaging according to waste hierarchy	None

2.2. *Life Cycle Assessment of Packaging*

Life cycle assessment is a process to evaluate environmental burdens associated with a product by quantifying the energy and materials used and the wastes and emissions released over the entire life cycle. ISO 14040 [40] and 14044 [41] provide a general framework and set minimum standards for the execution of an LCA. It is important to analyze the entire life cycle and to assess multiple impact categories to avoid burden shifting. LCA has become a decision-supporting tool in packaging design.

The first LCAs ever undertaken in the late sixties studied packaging [42]. Since then, a large number of packaging LCAs have been published [4], many of them being comparative [25,43–46].

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Most studies focus on the life cycle of packaging alone, without taking into account the interaction between the packaging and the packaged good. This issue is discussed in detail in the next subsection.

The first studies were not conducted in accordance to a standardized method. During the nineties, standardization took place; however, the ISO norms still leave a great deal of room for flexibility. Comparability between the results of different studies is severely limited, due to different modeling approaches, of which Table 2 gives an overview.

Table 2. Possible approaches in life cycle assessment (LCA).

Issue	Possible Approaches	References
General modeling approach	• Attributional • Consequential	[47,48]
End-of-life allocation procedure	• Recycled content/Cut-off • Avoided burden • 50/50 approach • etc	[49–54]
Database for secondary data	• GaBi • Ecoinvent • etc	[55–58]
Impact assessment methods	• CML • ReCiPe • TRACI • UBP 2013 • etc	[59]
System boundaries	Scope: • Cradle-to-grave • Cradle-to-gate • Gate-to-gate • Gate-to Grave • Geographical and temporal coverage of study • Cut-off criteria	[60,61]
Indicator selection procedures	• Correlation-based • Normalization w/o weighting • Normalization with weighting	[62,63]
Co-Product allocation	• Economic • Physical	[64]

This led to the development of EPD (Environmental Product Declaration) systems, which issue product category rules with narrowly defined system boundaries and predefined assessment methods to allow for comparability between studies. Hunsager et al. [65] analyzed 27 EPD programs and 556 product category rules. Even though they aim for harmonization, they increase proliferation due to their great number. There are generally no stand-alone product category rules for packaging, since packaging is rather regarded as an auxiliary for the studied product. A notable exception is the product category rule for closable flexible packaging [66].

Another attempt to harmonize LCA on an international level is The Life Cycle Initiative, hosted by the United Nations Environmental Program, which aims to provide a global forum for a science-based, consensus-building process [67].

The most ambitious initiative to harmonize LCA calculations and to improve comparability of results is the Product Environmental Footprint (PEF) initiative by the European Commission. The

European Commission published recommendations on the use of common methods to measure the life cycle environmental performance of products in 2013 [68]. These recommendations include a list of recommended impact assessment methods and an end-of-life allocation formula. This official document provoked criticism because the proposed end-of-life formula is not deemed suitable [69–72], some of the proposed impact assessment methods show a high degree of uncertainty [72,73] due to contradictions to the ISO 14044 standard [74]. Moreover, there are concerns that the PEF method will not lead to harmonization, but just be one of many approaches, and therefore even increase proliferation [72]. The Joint Research Center has refined the methodology and the latest Product Environmental Footprint Category Rules (PEFCR) Guidance document [75] recommends an improved end-of-life allocation formula and different impact assessment methods. Although a packaging working group exists, which defines calculation rules for packaging [76], no PEFCR for packaging have been developed, because it is a cross-cutting issue—such as transport services—which contributes to almost all product categories.

2.3. Inclusion of Packaging-Related Food Losses and Waste into Packaging LCA

Packaging-related food losses and waste refers not only to the amount of lost and wasted food, which could be prevented by optimized packaging but also includes the amount of lost and wasted unpackaged food which could be prevented by packaging.

There is an obvious relationship between packaging functionality and food losses and waste [77]. Packaging-related food losses and waste occur at different stages of the food supply chain [7]. Although the LCA community is increasingly aware of the fact that packaging-related food waste should be included in packaging LCA [8,10,78], it is to date not routinely included, since the rate of packaging-related FLW cannot be easily quantified.

Two possible approaches exist to include packaging-related food loss and waste into packaging LCA:

- Inclusion of lost and wasted food in packaging LCA.
- Calculation of the food-to-packaging (FTP) ratio.

The first approach requires the measurement of packaging-related food losses and waste. A certain percentage of the environmental impact of the packaged food is assigned to the packaging. Product loss rates have to be collected empirically. A correlation of food waste with a certain type of packaging can only be established if exactly the same product is packaged in two different packaging materials, or is available packaged as well as unpackaged, and different loss rates can be observed [9]. A quantification of packaging-related food losses and waste is possible for the losses due to fact that packaging is often difficult to empty. This is particularly important for food with a high viscosity, which is packaged in bottles or tubes [7]. If the rates cannot be assessed empirically, the practitioner must use assumptions. A large body of literature on food waste at the retail sector exists [79–81]. The reported numbers refer to the loss of packaged food, which is not necessarily packaging-related. It is challenging to assign a certain percentage of the loss of packaged food to poor packaging.

The environmental impacts of the production and disposal of packaging-related food waste can be calculated and compared with the environmental impacts directly caused by packaging [10], as shown in Figure 1.

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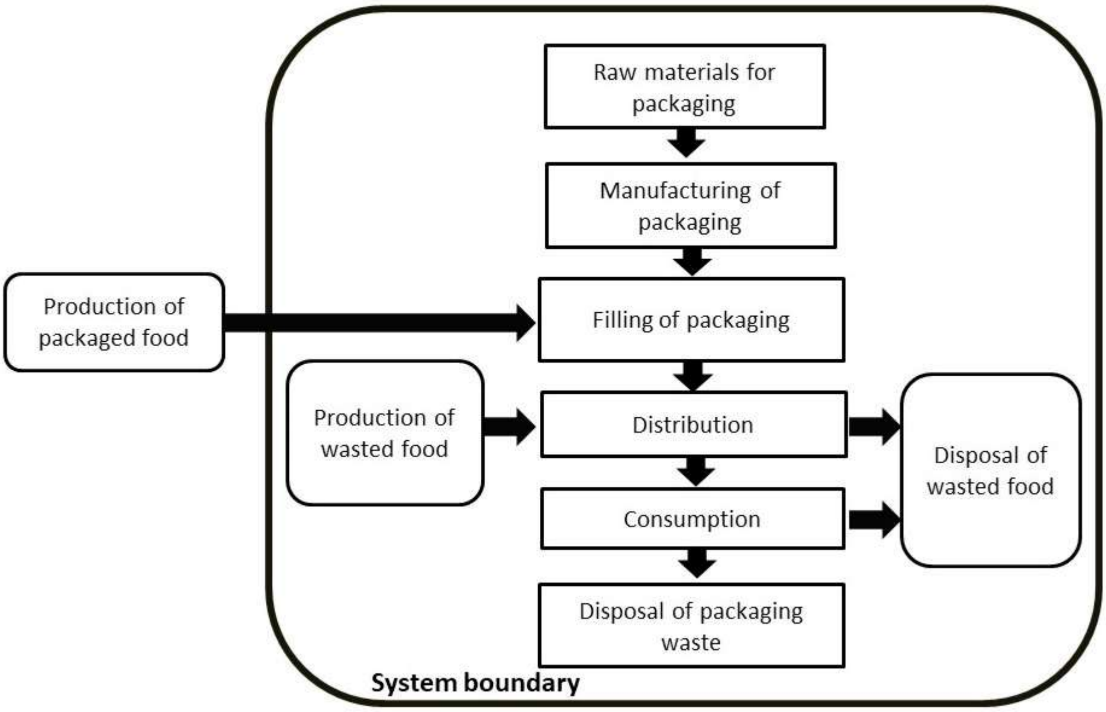

Figure 1. Inclusion of packaging-related food losses and waste (FLW) into packaging LCA (adopted from Grant et al., 2015).

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The second approach means that the environmental impacts of total packaged food are calculated and compared with the environmental impacts of packaging. This allows the calculation of the food-to-packaging (FTP) ratio. High ratios imply that packaging redesign should focus on optimized protection and food waste prevention. Very low FTP ratios indicate that packaging redesign should focus on light-weighting and recyclability [78]. The FTP ratio can be calculated regardless of whether data for packaging-related FLW is available or not. Food residues on disposed packaging cause environmental damage due to wasted food and their negative impact on the recyclability of packaging [13].

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2.4. Measuring the Circularity of Packaging

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The circular economy concept has been mainly been developed by practitioners and popularized by business foundations like the Ellen MacArthur Foundation. Currently, the EU, several national governments, and NGOs promote the concept. According to Korhonen et al. [14], a circular economy is characterized by maximizing the services produced from the linear nature–society–nature material throughput flow using cyclic material flows and renewable flow-based energy cascades. While materials can be cycled, useful energy is inevitably lost due to the laws of thermodynamics. In a circular economy, energy must be generated using renewable sources and utilized as efficiently as possible, e.g., by coproduction of heat and power. Korhonen et al. critically discuss the limitations of the concept and point to the fact that increasing the circularity of a given system may lead to burden shifting and adverse environmental effects elsewhere. Braungart and McDonough [15] classified cyclic material flows in two fundamental types: the biological and the technical cycle.

Circularity is understood here in a figurative sense and describes the contribution of a product to a circular economy. It refers to cyclic material flows and renewable energy flows. It builds on the definition given by Korhonen et al. and on the concept of biological and technical cycles [15]. Thus, a circular packaging is in the best-case reusable or, when produced from renewable or recycled materials and after its use, it is either recycled or composted [82,83]. It is produced, distributed, and recirculated entirely using renewable energy. Figure 2 illustrates the concept of circular packaging.

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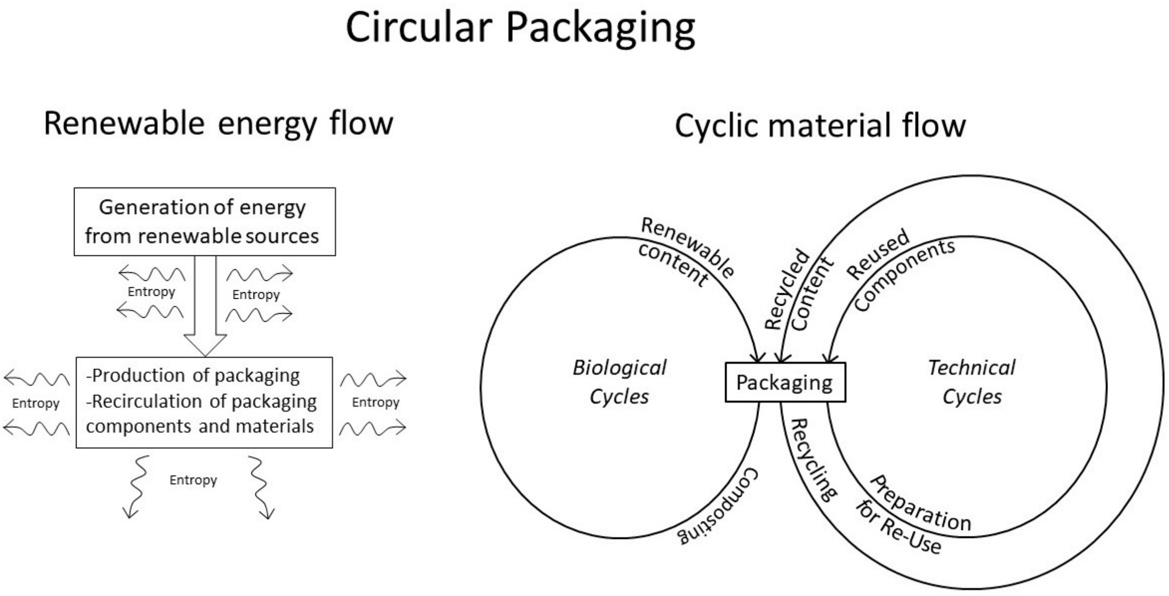

Figure 2. Circular packaging concept based on Korhonen et al. [14] and Braungart & McDonough [15].

This section gives an overview of circularity indicators relevant for packaging. This paper focuses on circularity indicators, which inform about material flows at the product level and the use of renewable energy. Measuring the circularity of packaging is highly relevant, due to higher legal requirements regarding the recoverability and actual recycling of packaging [17]. The indicators introduced below can be classified in three distinct categories. They refer either to material inputs or to material outputs or energy flows.

2.4.1. Input-Related Indicators

Input-related indicators refer to the materials used to produce a packaging. According to ISO 14021:2016, the recycled content is the proportion, by mass, of a recycled material in goods or packaging. Included in the definition is the use of postconsumer and preconsumer material. Excluded is the reutilization of materials such as rework, regrind or scrap generated in a process and capable of being reclaimed within the same process that generated it [84]. The reuse rate is input related as well as output related and is described below. While reuse and recycling refer to technical cycles, the use of biobased materials refers to biological cycles. The renewable content informs about the use of biological sources, which can only be called renewable if they are not used faster than they can be restored [85,86].

2.4.2. Output—Related Indicators

Output-related indicators refer to the fate of the materials after disposal of a packaging. The term “recyclable” can be interpreted in different ways. ISO 14021:2012 defines the term recyclable as a characteristic of a product that can be diverted from the waste stream through available infrastructure and can be returned to use in the form of raw materials or products [84]. Note that in this definition “recyclable” does not necessarily mean that the recycled material is used for the same purpose. On the contrary, the institute cyclos-HTP defines a recyclable packaging as a packaging, which can be recycled in a way that the recyclate replaces virgin material. Recyclability can be quantified as the mass ratio of recyclable material (expressed as a percentage). The recyclability metric, as defined by cyclos-HTP, takes into account losses during sorting and recycling [12]. While recyclability solely describes the potential of a packaging to be recycled, the recycling rate informs about the mass of packaging material, which is actually recycled. It is calculated by dividing the input of packaging waste to recycler by the total amount of packaging waste generated [17]. Recycling rates do not take the losses occurring

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during the recycling process into account. Therefore, another indicator is needed to quantify the actual output of the recycling operations. This is the percentage of a given packaging that is actually recirculated into the market as a secondary material. The parameter is called the recycling output rate [75] and is calculated by dividing the output of secondary material at the recycling plant by the total amount of packaging waste generated. In most cases recycling leads to a deterioration of the inherent properties of the material. This effect is called downcycling and can be calculated by dividing the quality of secondary material by the quality of primary material. The quality can be expressed either by price or by technical properties of the material. The downcycling factor is a prerequisite for LCA. While recycling is always associated with energy-intense remanufacturing, this is not the case with reusable packaging, although it has to be prepared for reuse before components can be reused. The most relevant indicator for reusability of packaging is the reuse rate, which refers to the total number of uses during the life of a packaging [75].

While recyclability and reusability refer to technical cycles, compostability refers to biological cycles. Composting of packaging in accordance with EN 13432 leads to the formation of H_2O, CO_2, and biomass in industrial composting facilities [36] and is classified as a recovery operation by European legislation [20].

2.4.3. Energy Indicators

The indicator "share of renewable energy" informs about the use of renewable energy for the production, use, and disposal of a packaging. It is calculated by dividing the amount of renewable energy by the total amount of energy consumed during the life cycle of a packaging. The amount of consumed energy can be characterized in different ways: either as final energy demand at the end-consumer or as cumulative energy demand [87].

2.5. Conflict of Interest between Different Sustainability Objectives

Sustainable food packaging causes low environmental impacts during production and disposal, provides optimal product protection, is easy to empty, and is as circular as possible. In reality, there are often trade-offs between these objectives. While using less packaging reduces the environmental impacts directly caused by packaging, this can lead to higher food wastage [9,29]. Although single use glass bottles are recycled more than PET bottles, they cause higher environmental impacts [43,46]. Multilayer plastic packaging is lightweight, efficient, and provides good product protection; however, it is in most cases not recyclable [24]. Optimization of one of the three aspects can lead to deterioration in another aspect.

3. Proposed Methodological Framework

The proposed framework defines minimum requirements for an extended life cycle assessment of packaging. It follows the consecutively explained guiding principles. This section outlines the guiding principles, defines requirements for LCA calculation and describes how the aspects of food waste and circularity can be included in the analysis. After introducing the guiding principles of the proposed framework, lists with recommended indicators with corresponding calculation procedures are given.

3.1. Guiding Principles for Methodological Choices

The assessment of packaging should always take into account the direct and indirect effects of packaging and should comprise additional information about the circularity of a packaging. Figure 3 illustrates the concept.

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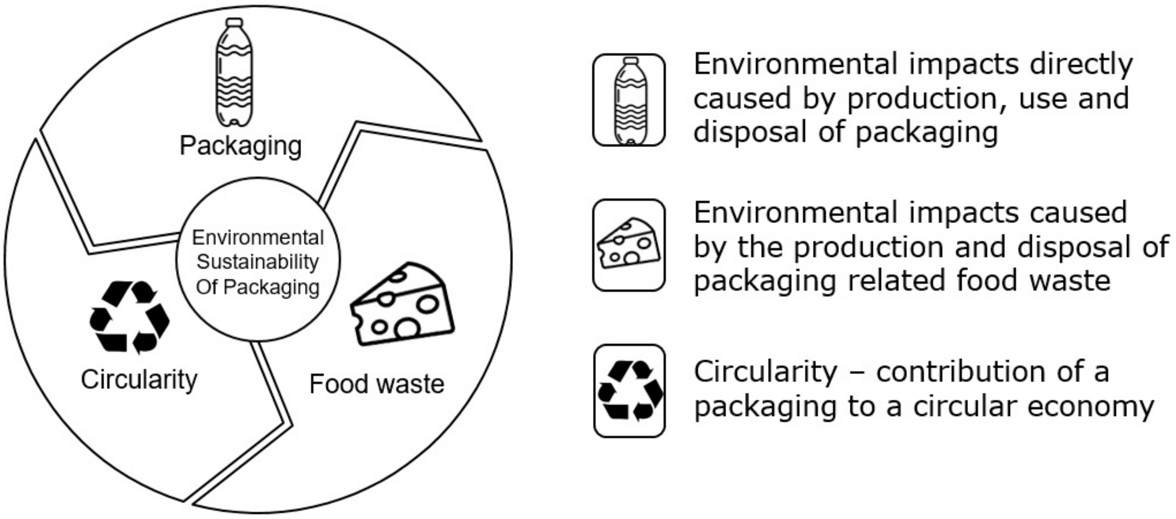

Figure 3. The three aspects of the environmental sustainability of food packaging.

The following proposed framework shall be set up of methods that are practicable and comprehensible. Practicability means that calculations can be conducted using standard LCA tools and datasets. In contrast to the abovementioned methodological frameworks, the here-proposed framework does not only describe general principles, it also explains how the relevant indicators should be calculated by referring to literature.

An important goal of this work is to streamline calculation procedures and assessed indicators to facilitate comparability. Therefore, practitioners should follow the latest PEF recommendations as far as possible. It aims to support business with complying with existing and forthcoming European regulation and standardization efforts. It explicitly refers to the Circular Economy Package of the EU and the PEF initiative.

Although many indicators can be calculated, the number of indicators should be reduced to a clearly arranged number of KEPIs suitable for decision-making processes, including product comparison and single-product optimization. Guidance on indicator selection processes is given in the following subsections.

3.2. *Basic Information Concerning the Packaging*

Alongside the results of the KEPIs, some basic information concerning the packaging and the validity of the calculated values must be reported:

- the weight, construction, and material composition of the packaging
- the functional unit of the studied system (quantified performance of packaging)
- the spatial and temporal validity of the calculated values

The results of life cycle impact assessment and recyclability assessment are only valid for a defined geographical region and refer to a specific time span [41].

3.3. *Recommendations for the Calculation of the Environmental Impacts Directly Caused by Packaging*

The procedures for calculating environmental impacts of packaging are oriented towards the latest recommendations published in the context of the environmental footprint pilot phase (European Commission, 2018). These recommendations might be subject to minor changes during the coming years. No standalone PEFCR exists for packaging, thus the recommendations given here are solely oriented to the PEF recommendations.

The full life cycle of the packaging should be modeled, considering the following life cycle stages.

- Raw material acquisition and preprocessing.
- Manufacturing of packaging.

- Manufacturing of packaging.
- Distribution.
- End-of-life.

For the calculation, primary data and PEF-compliant datasets for secondary data should be used. End-of-life of packaging has to be modeled using the Circular Footprint Formula. If no primary data are available for parameters such as recycling output rate or quality ratio, default values provided by the European Commission can be used. In this case, a sensitivity analysis should be performed to check how different end-of-life assumptions influence the total result.

The 16 recommended impact categories should be assessed and subsequently reduced to the three most relevant categories using the recommended normalization and weighting factors [88]. These three most relevant impact categories are used for decision-making and communication purposes. They are the basis for identifying the most relevant processes of a packaging's life cycle, which are those that contribute more than 80% to any of the most relevant impact categories identified. Table 3 presents a list of these 16 impact categories and the corresponding life cycle impact assessment methods.

Table 3. Recommended impact categories and corresponding assessment methods, adopted from European Commission [73,75].

Impact Category	Unit	Recommended LCIA Method
Climate change	kg CO_2 eq.	GWP100a, based on IPCC 2013
Ozone depletion	kg CFC-11 eq.	Steady-state ODPs
Human toxicity, cancer	CTUh	USEtox model
Human toxicity, noncancer	CTUh	USEtox model,
Particulate matter Ionizing radiation, human health	disease incidence kBq U235 eq.	PM method recommended by UNEP
Photochemical ozone formation, human health	kg NMVOC eq.	LOTOS-EUROS
Acidification	mol H+ eq.	Accumulated Exceedance
Eutrophication, terrestrial	mol N eq.	Accumulated Exceedance
Eutrophication, freshwater	fresh water: kg P eq.	EUTREND
Eutrophication, marine	fresh water: kg N eq.	EUTREND
Ecotoxicity, freshwater	CTUe	USEtox
Land use	Dimensionless (pt.)	Soil quality index, LANCA
Water use	m^3 world eq.	AWARE
Resource use, minerals, and metals	kg Sb eq.	CML 2002
Resource use, fossils	MJ	CML 2002

3.4. Recommended Indicators for Packaging-Related FLW

The environmental impacts of the packaged food should be calculated. Based on the greenhouse gas emissions, the FTP ratio [78] should be calculated by dividing the environmental impacts of food (E_{food}) by the environmental impacts of packaging ($E_{packaging}$).

The FLW rate is calculated by dividing the amount packaging-related FLW by the total amount of packaged food. Greenhouse gas emissions of packaging-related FLW have to be calculated.

Packaging properties do not directly influence FLW rates. Therefore, the amount of packaging-related FLW has to be collected empirically. To date it is not possible to determine exactly the rate of packaging-related FLW. We recommend a scenario-based approach to characterize the possible environmental impacts of packaging-related FLW in the case of lacking data. The amount of food wasted due to the inability to empty the packaging entirely can be determined by emptying a sample of packaging in a structured manner and weighing the residues. Literature data about the amount of packaged food wasted at retail and consumer level is available [79–81]. The PEFCR guidance document provides a list with default product loss rates [75]. Although scenarios can be derived from this data, they have to be interpreted with great care, since total loss rates generally exceed the packaging-related FLW rates.

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Additional qualitative information regarding packaging features that help to reduce FLW needs to be provided if relevant. These qualitative considerations refer to resealability, appropriateness of packaging size and protective properties of packaging. Table 4 presents a list of recommended indicators.

Table 4. Recommended indicators for packaging-related FLW.

Indicator	Metric	Recommended Assessment Method
Climate change result for packaged food (E_{food})	kg CO_2 eq.	GWP100a (IPPC 2013) [89]
Food-to-packaging ratio	Ratio $E_{food}/E_{packaging}$	Heller et al., 2018 [78]
Share of packaging-related FLW	Ratio Amount of packaging-related FLW/ packaged food (%)	Empirical data collection or literature based assumptions
Climate change result of packaging-related FLW	kg CO_2 eq.	Calculation: E_{food} multiplied by the share of packaging-related FLW
Protective properties of packaging	Description on packaging	Qualitative considerations
Appropriateness of packaging size	Description on packaging	Qualitative considerations
Resealability	Yes/No	Qualitative considerations

3.5. Recommended Circularity Indicators

The circularity indicators as listed below (Table 5) should be assessed if relevant for the studied packaging.

We recommend the use of qualitative recyclability assessment [90–93] in the form of an expert judgment, supplemented by semiquantitative [94] or purely quantitative approaches [12,35]. However, an evaluation of the recyclability has to consider country-specific characteristics of existing waste management systems and recycling infrastructure.

Table 5. Recommended circularity indicators.

	Indicator	Metric	Technical or Biological Cycles	Recommended Assessment Method
Input related	Recycled content	% of mass	Technical cycles	[84]
	Reuse rate	Number of usages	Technical cycles	[75]
	Renewable content	% of mass	Biological cycles	[30]
Output related	Recyclability	Expert judgment	Technical cycles	[12,35,90–94]
	Recycling rate	% of mass	Technical cycles	[17]
	Recycling output rate	% of mass	Technical cycles	[75]
	Downcycling factor	Ratio	Technical cycles	[75]
	Reuse rate	Number of usages	Technical cycles	[75]
	Compostability	Compliance with EN 13432	Biological cycles	[36]
Energy	Share of renewable energy	% of energy	Not applicable	[87]

3.6. Recommendations for the Interpretation of Results

Practitioners must clearly delineate the potential conflicts of interest revealed by the analysis. They should be well aware of the fact that—from an environmental point of view—reducing environmental impacts of the integrated food-packaging system is clearly preferable to improving the circularity of a product. Although packaging manufacturers are increasingly confronted with the demand for more recyclable packaging, they must always keep in mind that recyclability should not compromise the protective function of the packaging. The same is true for the use of renewable materials: they are more circular than fossil-based materials; however, they can lead to adverse environmental effects such as increased eutrophication [95].

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An important part of the interpretation is the analysis of the most relevant processes, which indicate the most effective levers for improvement. A sensitivity analysis demonstrates to which extent the results are influenced by assumptions.

4. Discussion

Packaging is under intense public scrutiny and regarded as a source of waste and pollution. Therefore, packaging producers are increasingly required to make packaging more sustainable. Most guidelines on packaging sustainability agree on a general definition of sustainable packaging. It has to provide optimal product protection, be safe for human health and cyclic while having the smallest possible ecological footprint.

Countless LCAs on food packaging have been conducted; however, few consider the interaction between the packaging and packaged food, although it is widely acknowledged that this interaction plays a key role for the environmental performance of food packaging.

The most important finding of this paper is that although many guidelines on packaging sustainability exist, detailed guidance on how to calculate KEPIs for packaging is surprisingly scarce which is why a measurement tool for packaging sustainability is required.

4.1. Demand for Standardization

The current proliferation of differing methods to assess the environmental performance of products leads to mistrust in environmental performance information and may increase cost for business [68]. Mandatory footprint information on products would influence consumer behavior and support sustainable purchasing decisions [96]. Such an approach would require a high degree of standardization of calculation procedures to allow for a fair comparison. As a result of this, the EU member states and industry requested the European Commission to develop a standardized European method for the calculation of the environmental footprint of products and organizations [97]. We support the goals of the PEF initiative and therefore the proposed measurement tool is oriented towards the PEF methodology. We acknowledge that there are challenges and that the criticism [72,98,99] is partly justified; in particular, the criticism regarding the as yet unclear policy outcome of the PEF process. Without clearly communicating the reason of developing another standard, there is a risk that the PEF initiative may even add to confusion and proliferation. Another problematic issue is cross-study comparability of results. A fair comparison between two products is only possible if the studies were conducted using exactly the same methodology, applying identical high quality standards regarding primary data and where full functional equivalency of the two products is given. Even if these two products are calculated using the same PEFCR and the same data basis for secondary data, it is—in practice—unlikely that all before mentioned requirements are met. This is a challenge of LCA studies in general and not specifically related to PEF, however, the PEF initiative may possibly lead consumers to compare products, which are not comparable. For good reasons, ISO 14044 requires high standards for comparative assessments. A harmonized approach can gradually improve comparability, but not provide full and fair cross-study comparability. Reproducibility and cost reduction will be achieved by reducing the number of methodological choices.

Some problematic issues of the original PEF proposal [68], for example the end-of-life allocation formula and inappropriate assessment methods for water and land use, have been addressed by the Joint Research Center, and significant improvements could be achieved [75]. The criticism directed to the PEF approach towards prioritization of impact categories using normalization and weighting [99] may be justified from a purely scientific point of view; however, in practice, prioritization of impact categories is carried out implicitly [97]. For example, a Product Carbon Footprint study attaches more importance to climate change than to other impact categories, although this may not always be justified. Steinmann et al. [63] elaborated an approach towards indicator selection based on an analysis of the correlation of impact category results and proposed a set of three indicators including land use, climate change, and human toxicity, because these indicators are the least correlated and cover a wide range of

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potential environmental implications. This science-based method avoids subjectivity, although it does not address the fact that environmental problems are not equally important [100].

Taken together, these arguments underline the importance of developing a harmonized European LCA approach, although there are still unresolved issues. Standardization would not only improve comparability and reproducibility of LCA calculations, it would be equally beneficial for the assessment of packaging-related FLW and circularity.

4.2. Reasons for Including Packaging-Related FLW

A growing body of literature has addressed the environmental relevance of packaging-related FLW. It has been shown, in some cases, that the environmental impacts of the production and disposal of wasted food by far exceeds the environmental impact of packaging [9]. In most cases, it is challenging or even impossible to determine the rate of packaging-related food losses and waste [7]. Therefore, even though data is restricted or non-existent, this paper aims to provide a systematic approach to include packaging-related FLW. A calculation of the food to packaging ratio can be conducted and a description of certain packaging features such as emptiability, resealability, and appropriateness of packaging size can be given nonetheless. A mandatory inclusion of this issue in packaging LCA can help to draw the role of packaging for food waste reduction strategies to the attention of packaging designers and retailers.

4.3. Reasons for Including Circularity

The main reason for including the abovementioned circularity indicators in sustainability assessment is that they are highly relevant for the environmental performance of packaging. They represent some of the most important levers to improve packaging sustainability, because packaging producers can directly influence parameters such as recyclability or share of used renewable energy. Moreover, it became a legal requirement to make packaging more circular. Nonetheless, the transition towards a circular economy is not a goal in itself; it should deliver ecological goals [101]. Packaging designers should always apply life cycle thinking to verify that, e.g., improved recyclability in fact contributes to the overarching goal of reduced environmental impacts.

The circularity metrics proposed in this paper focus on cyclic material and renewable energy flows. While most of the indicators can be assessed relatively easy, this is not the case for the recyclability assessment. A recyclability assessment requires a good understanding of the available recycling infrastructure and the suitability of a packaging to be reprocessed into a useful secondary material. For the determination of the downcycling factor, which is required for the calculation of the environmental burdens and benefits of recycling, it is necessary to understand the market situation of recyclables [70].

While many LCAs confirm the environmental benefits of reuse and recycling, the case is not so clear with biobased and compostable materials. The mechanical and barrier properties of biobased polymers have been significantly improved during the last years, which makes them increasingly suitable for food packaging [27]. Although biobased products decrease the dependency from fossil fuels, this may come at the price of more land use and other adverse environmental effects of agriculture [102]. Industry could overcome this drawback by using biowaste as a source for bioplastic precursors [103]. The European Union encourages the substitution of fossil raw materials with biobased materials as part of the bioeconomy strategy [104]. Compostability of packaging is often promoted as "environmental friendly" and a possible solution to the crisis of marine littering. According to the Waste directive 2008/98/EC, composting or reprocessing of organic material is a form of recycling. Compostable packaging generally only degrades in an industrial composting plant [105] and not in nature, therefore it is not a solution to the littering problem. It is problematic to define the composting of packaging as recycling because biopolymers do not contain plant nutrients and, therefore, their degradation does not lead to the formation of valuable manure. Rossi et al. [106] showed that mechanical recycling of polylactic acid would be preferable to composting. Moreover, compostable

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bags may cause problems in industrial composting plants, because they have to be manually removed owing to the fact that they are not easily distinguishable from conventional plastic bags [107].

The use of the material circularity indicator [86] is only optional because packaging designers should rather focus on identifying and improving the most relevant circularity metric. The material circularity indicator does not account for biological cycles, differing market situations for recyclables or the use of renewable energy. It credits product longevity, which is usually not relevant for food packaging.

4.4. Future Research and Data Requirements

The concept of packaging-related FLW needs further refinement. Future research should focus on the development of standardized procedures to quantify packaging-related FLW. Further work is required to collect data about packaging-related food losses and waste for different food categories and packaging types.

Further studies are needed to estimate how improvement of the proposed circularity indicators really reduces the environmental impact over the life cycle of packaging. This could be done by systematically analyzing different packaging. In doing so, circularity metrics can be adjusted to different values and by carrying out sensitivity analyses, the influence of metrics as recycled content, reuse rate, share of renewable energy on the results for the assessed impact categories can be estimated. This procedure could help to reveal the greatest levers for environmental improvement and potential conflict of interests. More data is needed for realistic estimations of recycling output rates for specific packaging types. The development of an open-source measurement tool for packaging recyclability would be highly beneficial for packaging designers and other interested parties along the packaging supply chain, including retailers and recyclers. This measurement tool should ideally cover all types of packaging materials, be adjustable to country-specific differences in waste management systems and allow for a quantitative assessment of packaging recyclability.

4.5. Conclusions

This paper has investigated how the environmental sustainability of food packaging can be defined and measured by appropriate indicators. The present research emphasizes the importance of developing a standardized measurement tool, which is in line with European environmental policy. The proposed KEPIs cover three different aspects of packaging sustainability: environmental impacts directly caused by packaging, environmental impacts caused by packaging-related food losses and waste, and circularity. This research has brought to light many questions which require further investigation, especially the unsolved question of how to quantify packaging-related FLW. Nevertheless, we believe our work provides a basis for further methodological developments.

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Sustainability of flexible multilayer packaging: Environmental impacts and recyclability of packaging for bacon in block

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ABSTRACT

Multilayer plastic packaging is difficult to recycle and perceived as an environmental problem, despite its valuable protective properties. This study examines environmental impacts and recyclability of six representative packaging solutions for bacon in block. Moreover, it takes into account the environmental impacts of the packaged product. The examined flexible packaging include two thermoformed films (polyamide (PA)/polyethylene (PE) & PE/ethylene vinyl alcohol (EVOH)), two vacuum bags (both PA/PE), and two shrink bags (PE/polyvinylidene dichloride (PVdC) & PA/EVOH/PE). A cradle-to-grave Life Cycle Assessment (LCA) was conducted. We assessed the recyclability of the different packagings by using the RecyClass tool, and compared the carbon footprint of the packaging with the carbon footprint of the packaged meat. The environmental impacts depend largely on the packaging weight and on the content of PA. Climate change results range from 26.64 g CO_2-equivalents for the PVdC-containing shrink bag to 109.64 g CO_2-equivalents for the PA-containing thermoformed film. Even if the recyclable PE/EVOH film is recycled, its climate change result (51.75 g CO_2-equivalents) is considerably higher than the result for the PVdC-containing shrink bag. Only the PE/EVOH film can be recycled, however, with considerable loss of quality. Carbon footprint of the packaged bacon is on average 54 times higher than carbon footprint of packaging. Given the relatively low environmental significance of packaging compared to the packaged meat, optimal product protection should be priority for packaging designers. Weight reduction is preferable to improved recyclability. We recommend assessing recyclability and impacts of the packaged good alongside with packaging LCA to highlight potential conflict of interests and to avoid burden shifting.

1. Introduction

Plastic packaging is perceived as an environmental problem, a source of litter and a contributor to climate change (Dilkes-Hoffman et al., 2019). Due to growing public pressure and stricter environmental legislation, great efforts are being made to reduce plastic packaging, despite its valuable protective properties. The industry puts great effort in the endeavour to improve the recyclability of plastic packaging. Recyclable packaging is perceived as more environmental friendly than non-recyclable packaging, however, this view is not always substantiated by Life Cycle Assessment. In response to these developments, the sustainability of plastic packaging has to be carefully scrutinized. The objective of this work is to analyse life cycle impacts and circularity of bacon packaging.

1.1. Bacon

Bacon is smoked and salted pork belly meat. Curing with nitrite is used for preservation. It has an antibacterial and antioxidant effect, stabilises the red pigment myoglobin, and gives bacon the typical taste (Feiner, 2016; Sofos et al., 1980). The attractive red colour of bacon stems from nitrosomyoglobin, which is formed by the reaction of nitrite with myoglobin. Although colour does not affect taste, it is very important for the consumer. A typical example is the traditional “Tiroler Speck” as described in regulation 2019/1027 (EC, 2019). Bacon is generally sold boneless, however, the surface can be hard and sharp-edged. Bacon is sold either in block or sliced. This study deals only with packaging of bacon in block, typically cut into more or less rectangular pieces of approximately 500 g.

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1.2. Packaging for bacon

Packaging must not only provide adequate barrier properties against oxygen and water vapour, but also offer the necessary mechanical stability (Bell, 2001; Feiner, 2016). Mazzola et al. (Mazzola and Sarantopoulos, 2020) recommend oxygen transmission rates from 20 to 50 cm^3/m^2/day and high puncture resistance for packaging suitable for sausages and cured meat. These requirements are best met by flexible multilayer packaging. By combining different materials, very thin films can meet diverse requirements. A typical combination is polyamide (PA) and polyethylene (PE). While PE is sealable and has low water vapour permeability, PA provides the necessary mechanical strength and reduces oxygen permeability. However, various combinations are conceivable. The packaging should also be attractive and transparent (Morris, 2016). Common packaging systems for bacon in block are thermoformed films, vacuum bags, and shrink bags (Bell, 2001).

1.3. Packaging sustainability

In addition to the aforementioned requirements, packaging must also meet certain sustainability criteria. Sustainable packaging should provide optimal product protection. Furthermore, the environmental impacts through the life cycle of the packaging should be minimized. Ideally, sustainable packaging is safe for the environment and humans, and as circular as possible (Verghese et al., 2012). Product protection is the central criterion for sustainable packaging in the meat sector, because the environmental impact of the packaged product is far greater than the environmental impact of the packaging (Heller et al., 2019; Pilz, 2017). Savings in packaging, which lead to higher levels of food waste, can significantly worsen the environmental impacts of the integrated product packaging system.

However, as far as product protection is guaranteed, the greatest possible packaging efficiency should be ensured, i.e. unnecessary overpackaging should be avoided, and the use of toxic substances must be prevented. The revised European Waste Framework Directive anchors the five-step waste hierarchy (prevention, preparing for re-use, recycling, other recovery, disposal) in law (EP & Council, 2018b). Disposal of packaging in accordance with the waste hierarchy helps to keep impacts low. In some cases, deviations are admissible, if life cycle assessment (LCA) results show that waste incineration with energy recovery is more resource efficient than mechanical recycling (EP & Council, 2018b) for example.

Circular packaging is made either from renewable or recycled materials. After use it is either recycled, reused or composted. Only renewable energy should be used in its manufacture (Pauer et al., 2019). Due to the amendment of the Packaging Directive in the EU, the discourse is primarily about improved recyclability. The mandatory recycling rate for plastic packaging will be increased from 22,5%–55% by 2030 (EP & Council, 2018a). Within the framework of the New Plastics Economy Global Commitment, numerous packaging manufacturers, consumer goods producers and trading companies have declared to drastically reduce their plastic packaging, or to make it either recyclable, compostable, or reusable (Ellen MacArthur Foundation, 2018). Among the signatories are many producers of flexible multilayer packaging, which results in growing pressure on manufacturers and users of flexible packaging. Flexible multi-layer films are difficult to recycle since the layers cannot be separated with economically justifiable effort. Many research initiatives are concerned with improving the recyclability of these flexible films (CEFLEX, 2020; Fraunhofer IVV, 2020).

LCA is the method of choice for assessing packaging sustainability. In the case of packaging, however, LCA should be accompanied by circularity assessment and consideration of the environmental impacts of the packaged product (Pauer et al., 2019). This holistic approach avoids burden shifting. An exclusive focus on a single indicator like carbon footprint or recyclability always bears the risk of missing important environmental aspects.

1.4. Literature overview

Several studies deal with the life cycle assessment of flexible packaging and meat packaging. Siracusa et al. (2014) conducted an LCA of a PA/PE vacuum bag with a layer thickness of 85 μm. The authors highlight the importance of reducing the film thickness to avoid unnecessary environmental burdens, as long as the necessary food protection is provided. Büsser et al. (2009) examined the role of flexible packaging in the life cycle of butter. They demonstrated that packaging does not significantly contribute to the total life cycle impacts of butter. Maga et al. (2019) analysed different rigid trays for meat. Trays made of extruded polystyrene (XPS) perform better than PET, rPET or PLA trays. Even if higher recycling rates were realised in the future, XPS solutions would still perform best from an environmental perspective. This study shows that the end-of-life stage plays an important role, however production of raw materials dominates. Similar to Siracusa et al. (2014) the authors stress the importance of weight reductions. Barlow et al. (2013) reviewed several LCA studies on flexible packaging and concluded that minimization of material used whilst retaining mechanical and barrier properties should be clearly prioritized over recyclability improvements. These findings are underlined by a study (Flexible Packaging Europe, 2020), showing that replacement of non-recyclable, but light-weight flexible packaging with recyclable monomaterial packaging would increase environmental burdens. Pilz (2017) compared various packaging solutions for products such as beef and cheese, and also accounted for packaging related food losses. The results clearly show that food loss prevention is by far more important than the minimization of the impacts of the packaging itself. Taken together, these studies suggest that food loss prevention is the top priority in ecodesign of meat packaging, and that lightweighting should be prioritized over circularity improvements.

There is a growing interest in the recyclability of multilayer flexible packaging. Kaiser et al. (2018) highlight the difficulties of multilayer packaging recycling and describe the state of the art techniques of delamination of the different layers and compatibilization of nonmiscible polymers. Although technically feasible, these techniques are not common on industrial scale. Blends of immiscible polymers can be recycled by the use of compatibilizers (Ragaert et al., 2017; Uehara et al., 2015). Chemical recycling can be a possible solution for multilayer packaging. It includes chemolysis and pyrolysis. Chemolysis is feasable for condensation polymers like PET and PA and allows for the production of valuable monomers, suitable for food grade applications. Pyrolysis of mixed plastics allows for the production of waxes, gaseous and liquid fuels. Pyrolysis and chemolysis have to be operated on large scale to be economically viable (Ragaert et al., 2017). Van Eygen et al. (2018) describe the current situation of plastic packaging recycling in Austria, and show that small plastics films are predominantly incinerated.

Several authors point out, that the amount of packaging-related food losses and waste is a key indicator for the assessment of packaging sustainability, although precise numbers are hard to obtain (Wikström et al., 2019; Wohner et al., 2019). Lebersorger and Schneider (2014) report loss rates of 2.39% for sausages and cured meat at the retail stage. This category also includes products sold at the deli counter with relatively high loss rates (Pilz, 2017), eg. freshly sliced sausages or ham. These products are much more susceptible to microbial decay and drying than packaged bacon in block. Moreover, not all the meat products, which are lost at retail level are lost due to poor packaging. Therefore, we assume that packaging-related loss rates for bacon in block are significantly lower than 2.39%.

There are no published studies on the environmental effects of packaging for bacon in block. There are several studies that deal with either multilayer packaging or meat packaging. However, these do not systematically cover the aspects of circularity and the environmental impact of the packaged product.

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1.5. Goal and research question

The aim of this study is to analyse life cycle impacts and circularity of common mulitlayer packaging for bacon in block. Furthermore, we compare the environmental impacts of packaging with those resulting from the packaged product. This analysis deals with primary packaging and refers to the situation in Austria in the year 2019 exclusively. Although the present study focusses on existing systems, an outlook on new developments is given in the discussion section.

Furthermore, the authors aim at establishing a holistic approach towards the assessment of packaging sustainability. This approach combines LCA with circularity assessment and the consideration of the environmental impacts of the packaged product. The goal of this approach is to avoid burden shifting, to enable environmentally sound decisions, and ultimately to contribute to cleaner environmental systems. By doing so, the abovementioned research gaps are adressed.

2. Packaging systems

Commonly used packaging systems for bacon in block include thermoformed films, vacuum bags, and shrink bags (Bell, 2001). For each of these basic types, two variants, differing in layer composition and thickness, are introduced. All six variants are multilayer films, primarily produced by coextrusion. Information concerning the layer thicknesses are always given in μm, specifications for layer compositions start with the outer layer. Oxygen and water vapour transmission rates are reported along with the testing method. When comparing values, it must be taken into account that various testing methods were used. The assumptions that the used PE is linear low density polyethylene (LLDPE) and the used PA is polyamide 6 are based on Morris (2016). End-of-Life assumptions are based on Van Eygen (2018). Due to the landfill ban for plastic waste in Austria (Deponieverordnung, 2008, 2008/2020), non-recyclable post-consumer packaging waste is utilised for energy recovery. Production waste of monomaterial plastic films (eg. cutting waste) is assumed to be recycled. Data on bacon packaging was requested from different manufacturers. Because packaging manufacturers did not disclose every detail, some literature-based assumptions were made (Morris, 2016). We do not disclose specific product names or companies in this publication for confidentiality reasons. The appendix contains inventory data, assumptions, data sources, flow diagrams and graphical representations of the packaging types.

2.1. Thermoformed films

The packaging consists of two components, a forming film and a nonforming film. After the forming film is thermoformed, the product is placed in the trough. Finally, the nonforming film is placed on top and the whole is vacuumed and sealed. After use, the film is usually disposed of in the residual waste and sent to waste incineration. As the forming film is deep drawn, it must be thicker than the non-forming film. The advantage of the thermoformed two-part packaging is its consumer appeal (Morris, 2016). However, significantly more material has to be used than for the other variants since thermoforming reduces the wall thickness in some places and increases oxygen permeability (Buntinx et al., 2014). Two variants of this system are investigated.

2.1.1. Thermoformed film - PA/PE (1a)

This packaging is typical for cured bacon sold in supermarkets. It consists of amorphous polyethylene terephthalate (A-PET), PA and PE. Table 1 shows properties and material composition of this variant.

2.1.2. Thermoformed film – polyolefins (PO)/EVOH (1b)

This thermoformed film has been optimized for recyclability. It consists of oriented polypropylene (OPP), PE and an oxygen barrier layer of ethylene vinyl alcohol (EVOH) (see Table 2).

Table 1
Properties and material compostion of PA/PE thermoformed film (1a).

Property	Parameter
Layers of nonforming film	A-PET/PE/PA/PE - 23/50/40/50 (163 μm)
Layers of forming film	PE/PA/PE 120/90/120 (330 μm)
Label	Graphic paper
Weight of packaging	14.04 g
Oxygen transmission rate	16 cm^3/m^2 d bar (23 °C, 50% relative humidity - DIN 53380)
Water vapour transmission rate	3 g/m^2 d (38 °C, 90% relative humidity - DIN 15106-2)
Puncture resistance	95 N (23 °C, 50% relative humidity – ASTM F 1306-90)

Table 2
Properties and material composition of PO/EVOH thermoformed film (1b).

Property	Parameter
Layers of non-forming film	OPP/PE/EVOH/PE 35/80/5/80 (200 μm)
Layers of forming film	PE/EVOH/PE 145/10/145 (300 μm)
Label	Graphic paper
Weight of packaging	13.22 g
Oxygen transmission rate	4 cm^3/m^2 d bar (23 °C, 0% relative humidity - DIN 53380)
Water vapour transmission rate	not available
Puncture resistance	10 N (DIN EN 14477)

2.2. Vacuum bag

A bag is formed from a PE/PA composite film. Sealed-edge or tubular bags are used for bacon. After placing the product in the bag, it is vacuumed and sealed in a chamber machine. During this process, flexible packaging collapses around the bacon, which creates a preservative, oxygen-deficient environment (Bell, 2001). Upon unpacking, the film is sent to municipal incineration. Packaging with vacuum bags requires fewer process steps than packaging with thermoformed films. As shown in Tables 3 and 4, the two variants (2a, 2b) only differ in thickness.

2.3. Shrink bag

A bag is formed from shrinkable composite films. These films are oriented and stretched during polymer processing. The film is cooled, and the orientation is frozen in place. After reheating, polymer chains relax back into their preferred configuration, causing shrinkage (Morris, 2016). Labelling takes place before the product is placed in the shrink bag. The product is placed in the bag, shrunk and sealed under the influence of heat. During the shrinking process, oxygen also escapes. After use, the film is disposed of in the residual waste and sent to municipal incineration (Van Eygen et al., 2018).

2.3.1. Medium abuse barrier shrink bag (3a)

This shrink bag consists of polyvinylidene dichloride (PVdC) and PE. According to the manufacturer this shrink bag is suitable for hard surface meats due to its high puncture and abrasion resistance, without data being disclosed regarding mechanical properties. Table 5 presents the properties of this PVdC-containing shrink bag.

Table 3
Properties and material composition of 145 μm vacuum bag (2a).

Property	Parameter
Layers	PA/PE 30/115 (145 μm)
Label	Graphic paper
Weight of packaging	8.2 g
Oxygen transmission rate	40 cm^3/m^2 d bar (ISO 15105-1)
Water vapour transmission rate	3 g/m^2 d (calculated)
Puncture resistance	Not available

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Table 4
Properties and material composition of 90 µm vacuum bag (2b).

Property	Parameter
Layers	PA/PE 20/70 (90 µm)
Label	Graphic paper
Weight of packaging	5.3 g
Oxygen transmission rate	$< 60\ \mathrm{cm}^3/\mathrm{m}^2$ d bar (23 °C, 0% relative humidity; ISO 15105-1)
Water vapour transmission rate	$< 4\ \mathrm{g/m}^2$ d (calculated)
Puncture resistance	Not available
Tensile strength – Longitudinal/ Transverse	$\geq 35/\geq 25$ N/15 mm (DIN 53455-6)

Table 5
Properties and material composition of PVdC-containing shrink bag (3a).

Property	Parameter
Layers	PE/PVdC/PE 36/3/36 (75 µm)
Label	Graphic paper
Weight of packaging	4.4 g
Oxygen transmission rate	$16\ \mathrm{cm}^3/\mathrm{m}^2$ d bar (method not disclosed in data sheet)
Water vapour transmission rate	$8\ \mathrm{g/m}^2$ d (method not disclosed in data sheet)
Puncture resistance	Not available
Shrink	45/49%

2.3.2. *High abuse barrier shrink bag (3b)*

This shrink bag contains EVOH and PA, therefore combining good mechanical stability with excellent oxygen barrier. According to the manufacturer, this shrink bag provides very high puncture resistance, without data being disclosed regarding mechanical properties. Table 6 presents the properties of this EVOH-containing shrink bag.

3. Methods

3.1. *Life cycle assessment*

3.1.1. *Calculation procedure*

The calculation of the potential environmental impacts is oriented towards ISO 14040/44 (ISO, 2006) and the Product Environmental Footprint Category Rules (PEFCR) guidance document issued by the European Commission (EC, 2018).

3.1.2. *Functional unit*

The functional unit for the present study is 550 cm^2 multilayer film for packaging of 500 g of bacon, representing a typical size on the market. The system under investigation includes the production and disposal of the primary packaging. For the production, data sets were selected that correspond to an European average. This is representative for Austria, because as a small landlocked country it imports numerous packages and packaged products. The disposal scenarios refer to the situation in Austria in the year 2019. The use phase is not part of the study, as energy for cooling is attributed to the bacon and not to the packaging. Although functional additives are important for the manufacturing of plastic packaging, their amounts are negligible (Cherif Lahimer et al., 2017; Hahladakis et al., 2018) and therefore excluded from this analysis.

Table 6
Properties and material composition of PA/EVOH/PE shrink bag (3b).

Property	Parameter
Layers	PA/Tie/EVOH/Tie/PE 30/5/5/5/55 (100 µm)
Label	Graphic paper
Weight of packaging	5.9 g
Oxygen transmission rate	$12\ \mathrm{cm}^3/\mathrm{m}^2$ d bar (method not disclosed in data sheet)
Water vapour transmission rate	Not available
Puncture resistance	Not available
Shrink	40/46%

3.1.3. *Environmental impact categories*

The ecoinvent 3.6 cut-off database (ecoinvent Association, 2019) was used to calculate potential environmental impacts. This database is the most comprehensive life cycle inventory database available, and contains all the necessary datasets to calculate both the environmental impacts of the packaging itself and of the packaged product. Further details about the used datasets are disclosed in the appendix. The software openLCA 1.9 (Green Delta, 2019) was used, and assessments were performed with the impact assessment method ILCD 2.0 2018 midpoint. The allocation method used is the “Circular Footprint Formula” as recommended by the European Commission. We choose this allocation approach, because it fairly credits End-of-Life recyclability and takes quality losses of the resulting recyclate into account. The impact categories evaluated also comply with the PEFCR guidance document. By normalisation and weighting, the most important impact categories (Table 7) were determined for each variant studied. The normalisation and weighting factors of the PEFCR guidance document (EC, 2018) were used. The nomenclature of the impact categories slightly differs between the ILCD method as implemented in openLCA and the PEFCR guidance document.

3.1.4. *Scenario and sensitivity analysis*

Due to uncertainties or variability of the true value of input parameters, certain assumptions have to be made. By varying the input parameter, the effect on the overall result can be determined.

Three different recycling scenarios for thermoformed film 1b are compared. The recycling rates of 0%, 18% and 72% refer to the recycling output rate, i.e. to the mass percentage that can actually be recycled into regranulate. The rates relate exclusively to the recycling of post-consumer waste.

- Standard scenario 0%: post-consumer waste goes to waste incineration
- Best case 18%: Current value for small films in Austria (Van Eygen et al., 2018)
- Best case 72%: Optimistic assumption - all films are collected and correctly sorted, but recycling efficiency is 72% (Van Eygen et al., 2018)

Moreover, we examine to which extent the use of low density polyethylene (LDPE) instead of LLDPE affects the total results. The baseline assumption for the energy used for shrinking is derived from a patent (Schilling, 2011). According to the PEFCR guidance, the default distance to be used for transport of packaging material from manufacturer to filler is 230 km (EC, 2018). Truck transport is assumed. Shrink tunnels vary greatly regarding their energy efficiency, and transport distances can vary. Therefore, a sensitivity analysis was carried out for these parameters (Table 8).

Table 7
Impact categories considered in this study, based on European Commission (EC, 2018).

Impact category	PEFCR name	Unit	Description of indicator for the impact category
Climate change	Climate change	g $\mathrm{CO_2}$- eq.	Elevated radiative forcing (Global warming potential for 100 years)
Freshwater eutrophication	Eutrophication, freshwater	g P – eq.	Harmful nutrient input to freshwater ecosystems
Fossil resources	Resource use, fossils	MJ	Resource depletion for fossil fuels
Respiratory effects	Particulate matter	Disease incidence	Health effect of air pollution

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Table 8
Scenario analysis.

Parameter	Variants	Baseline assumption	Scenarios
Recycling output rate	1b	0%	0%, 18%, 72%
Transport distance	all	230 km	0 km–1000 km
PE Input	all	LLDPE	LDPE instead of LLDPE
Energy for shrinking	3a + 3b	0.0139 kWh/piece	0 to 0.05 kWh/piece

3.2. Circularity

According to the definition of circular packaging (Pauer et al., 2019), there are several circularity indicators. As the examined packaging systems are neither bio-based nor compostable nor reuseable, the evaluation of circularity is limited to two indicators, namely recyclability and use of renewable energy throughout the life cycle.

3.2.1. Recyclability assessment

The recyclability of the films was calculated using the RecyClass method (Plastics Recyclers Europe, 2020). This evaluation methodology refers to the situation in the EU and is a free-to-use online tool. The user is prompted to provide information on material composition of the packaging. RecyClass is only suitable for packaging which is made of plastic, is free from hazardous substances, and does not consist of oxo- or bio-degradable plastic. Furthermore, incompatibilities that affect recycling efficiency are verified. There are questions regarding the use of recycled material, the emptiability, and REACH compliance. The online questionnaire corresponds to the recyclability guideline for PE films, where the recyclability criteria are defined (Plastics Recyclers Europe, 2019a).

After completion of the online questionnaire, the packaging is classified into one of the categories shown in Table 9.

Additionally, a qualitative description of collection, sorting, and mechanical recycling of multilayer films in Austria is given.

3.3. Share of renewable energy sources

One of the essential criteria for a circular product is the use of renewable energies in the manufacture, use and disposal of a product (Korhonen et al., 2018; Pauer et al., 2019). The share of renewable energies in the life cycle of multilayer films is indicated by "cumulative energy demand" (Frischknecht et al., 2015; Hirschier and Weidema, 2010). The value describes the amount of energy that is taken from nature and also includes the energy contained in the materials. The results distinguish between renewable and non-renewable energy sources.

3.4. Food-to-packaging ratio for environmental impacts

The Food-to-Packaging (FTP) ratio describes the relationship between the environmental impact of the packaged product and the packaging (Heller et al., 2019). The value provides qualitative indications of what a sustainable packaging design should focus on. Very high values indicate that the focus should be on maximum product protection. Very low values may indicate a potential for reducing the weight of the packaging or improving recyclability. The FTP ratio is only calculated for the impact category "Global warming - GWP100″, as most reliable and methodologically comparable literature values are available for this category. The following formula calculates the FTP ratio:

$$FTP\ ratio = \frac{Environmental\ impact\ of\ meat}{Environmental\ impact\ of\ packaging}$$

Several studies on pork production were considered in the context of this study (Blonk et al., 2009; Djekic et al., 2015; MacLeod et al., 2013; Müller-Lindenlauf et al., 2013; Röös et al., 2013; Thoma et al., 2011). The studies differ considerably in terms of the functional unit. The selection criterion was a suitable functional unit, which includes not only meat production but also burdens from further processing and distribution. Furthermore, the selected study should be as representative as possible for the situation in Central Europe. For this study, the value of 5 kg CO_2 eq/kg pork was used for the calculation (Müller-Lindenlauf et al., 2013). This value refers to the production, processing and distribution (including refrigeration) of high-quality pork in Southern Germany.

Table 9
Recyclability classification according to RecyClass (Plastics Recyclers Europe, 2020).

Class	Description
A	The package does not pose any recyclability issues and can potentially feed a closed-loop scheme to be used in the same application.
B	The package has some minor recyclability issues and could even potentially feed a closed-loop scheme
C	The package has some recyclability issues that affect the quality of its final recyclate.
D	The package has some significant design issues that highly affect its recyclability.
E	The package has major design issues that put its recyclability in jeopardy.
F	The package is not recyclable either due to fundamental design issues or a lack of specific waste stream widely present in the EU.

4. Results

4.1. Environmental impacts of the examined packaging

4.1.1. Results for the six variants

The results show a strong positive correlation between packaging weight and potential environmental impacts for the categories climate change, fossil resources, and respiratory effects. Consequently, raw material production dominates the overall result. The freshwater eutrophication result significantly depart from this pattern, since energy requirements for the manufacturing has a stronger influence on the overall result than raw material consumption. Figs. 1–4 show the potential environmental impacts of the six examined variants. The bars also indicate the contribution of the life cycle phases raw materials, manufacturing and End-of-Life (EoL). Manufacturing includes burdens from transport.

In the climate change category, raw materials dominate the life cycle impacts of the examined packaging (see Fig. 1). The packaging with the lowest carbon footprint is the PE/PVdC shrink bag (variant 3a).

Fig. 2 shows the freshwater eutrophication results. There are remarkable high values for manufacturing and credits (negative impacts) for the End-of-Life stage. This is due to the consumption of electrical energy during processing, and crediting of electricity at the waste incinerator. This is explained in detail in the discussion section.

As shown in Fig. 3, the fossil resources category is predominantly dominated by raw material consumption, due to the fact that conventional plastic packaging is made of fossil resources.

Raw materials and processing contribute to the respiratory effects category, while End-of-Life is negligible for air pollution (see Fig. 4). As with the other impact categories, the thermoformed PE/PA film has the highest result for respiratory effects.

4.1.2. Recycling scenarios (1b)

Two additional recycling scenarios were calculated for the thermoformed polyolefins film (1b). A recycling output rate of 18% leads to 7% lower greenhouse gas emissions. In the best case (72% recycling output rate), these emissions are reduced by 27% compared to the standard scenario with 0% post-consumer recycling (see Fig. 5).

Fig. 6 shows the relative changes of different EoL scenarios for the four impact categories.

4.1.3. Sensitivity analysis

Fig. 7 shows the relative change in the overall result as a function of

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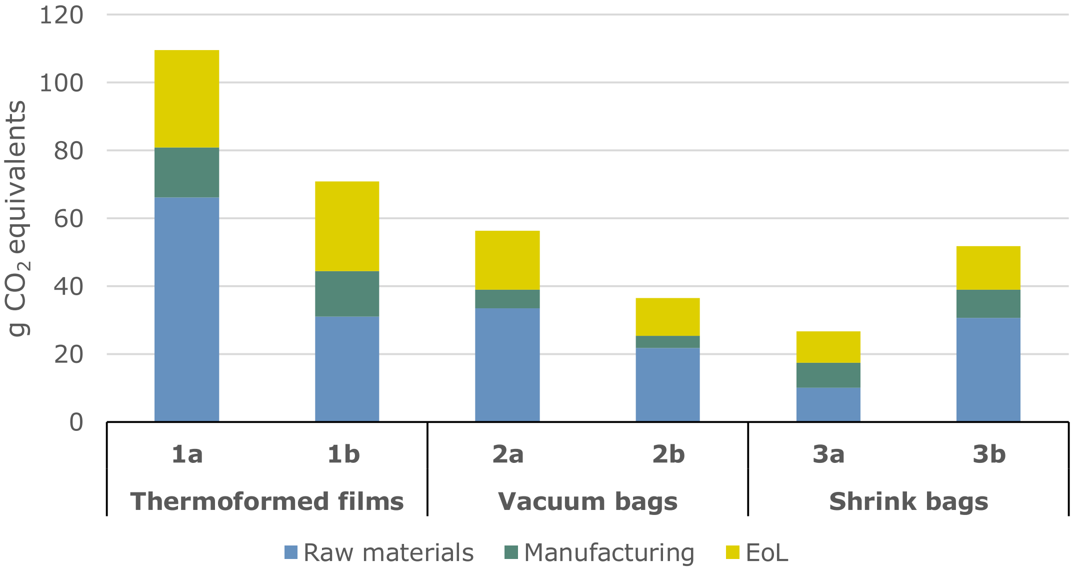

Fig. 1. Climate change results.

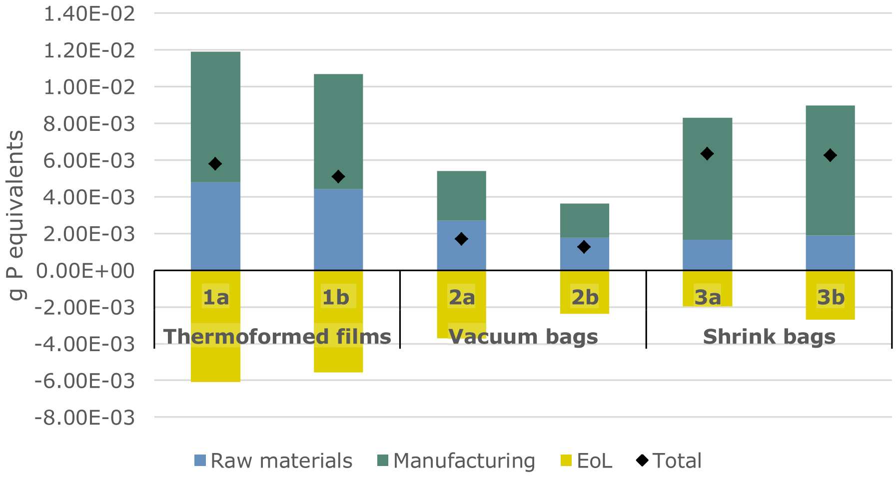

Fig. 2. Freshwater eutrophication results.

the transport distance. To achieve this, the deviations for the individual scenarios were calculated and the values averaged. A change in transport distance of 100 km leads (on average for the six variants) to a change of 0.25% in the overall result for climate change. For the respiratory effects category, however, the change is 0.6% per 100 km.

The use of LDPE instead of LLDPE leads only to minor changes for the categories climate change, respiratory effects and fossil resources. Again, the freshwater eutrophication result deviates from this pattern (Fig. 8).

Fig. 9 shows that the freshwater eutrophication result is highly sensitive to assumptions regarding energy consumption for the manufacturing of shrink bags.

4.2. *Circularity*

4.2.1. *Recyclability*

Only the thermoformed PE/EVOH is classified as recyclable, whereas the other variants are not recyclable. The main reason for classifying variants 1a, 2a, 2b, 3a, and 3b as “not recyclable” is that the dominant material PE comprises less than 95%, and that the inseparable components do not exclusively consist of PE and PP. Variant 1b is classified as recyclable in RecyClass, although the quality of the recyclate is affected by the use of various materials (Table 10).

Collection: It is possible to dispose of all lightweight plastic packaging separately, by kerbside collection or in collection stations in many Austrian regions (BMV - Burgenländischer Müllverband, 2020). In many municipalities, including Vienna, only plastic bottles are collected, and films must be disposed of in the residual waste, whereupon they are sent for thermal treatment (Municipal Department 48 of Vienna [Waste Management], 2020). Therefore, such films are not collected nationwide.

Sorting: The films 1a, 2a, 2b, 3a and 3b contain well over 5% PA or PVdC and can therefore not be assigned to a recycling stream. Only the polyolefin/EVOH film (1b) can be assigned to a polyolefin fraction. In Austria, PP films are not recycled but assigned to a recovered solid fuels (RSF) fraction and incinerated (Van Eygen et al., 2018). Therefore, the OPP layer of the top film is also a problem during sorting.

Recycling: Theoretically, the valuable polyamide can be released from the compound and recovered (APK, 2020). However, this is neither common practice in Austria nor is it done on an industrial scale. Shrink

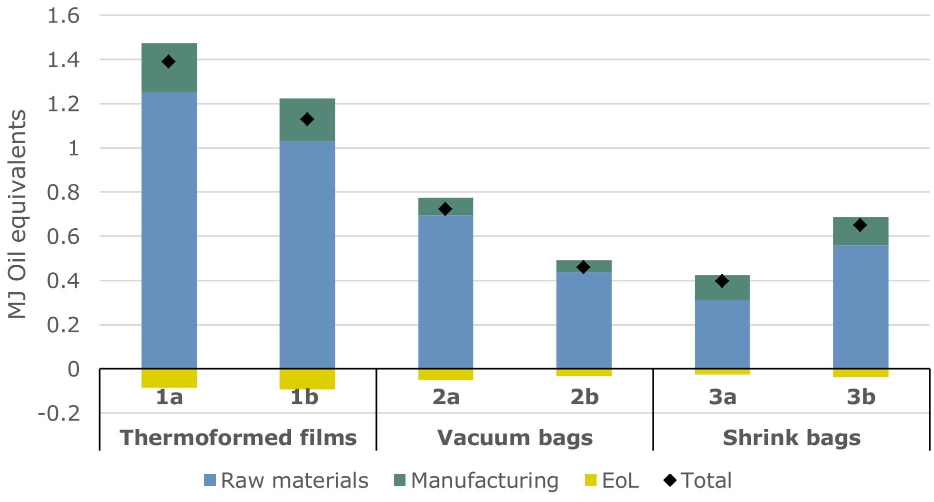

Fig. 3. Fossil resources results.

bag containing PVdC is also not recyclable (FH Campus Wien, 2019). Chlorine is toxic and can lead to contamination of the recycled material (Park et al., 2007). The polyolefin/EVOH film is classified as recyclable, because it is in principle possible to produce a secondary granulate from this material. However, this leads to a significant reduction in quality. On the one hand PE and PP are susceptible to oxidation, on the other hand PE, PP and EVOH mix poorly (Li et al., 2009; Tall et al., 1998). This leads to a significant loss of quality. The processability and mechanical properties of recycled mixed polyolefins are significantly worse than those of pure primary material (Tall et al., 1998). This regranulate is therefore not available for high-quality applications in the food packaging sector.

4.2.2. *Share of renewable energy sources*

Share of renewable energies was calculated according to Frischknecht et al. (2015). The calculated values for our tested packaging material range from 3.4% to 12.2% with a mean value of 6.1%, which is lower than the share of renewable energies in the EU energy mix (18.9% in the EU in 2018) (eurostat, 2020). The reason for these low values is the fact that the cumulative energy demand method chosen here also accounts for the energy contained in the materials.

4.3. *Food to packaging ratio*

The calculated FTP ratios demonstrate the low environmental significance of plastic packaging compared to meat production. The FTP ratio for climate change ranges from 23 (variant 1a) to 94 (3a), with an average of 54 (further details see appendix). That means, that only about 2% of environmental impacts of the combined food-packaging-systems can be attributed to the plastic packaging. The higher the FTP ratio, the lower the environmental impact of the packaging relative to the packaged meat. Since a product is compared here with different packaging variants, high values indicate relatively low environmental impacts of the packaging.

5. Discussion

5.1. *Environmental impacts of the examined packaging*

This life cycle assessment examined six different variants of multilayer packaging for bacon in block: a thermoformed PA/PE film (1a), a potentially recyclable polyolefin film (1b), two PA/PE vacuum bags with different layer thicknesses (2a + 2b), a PE/PVdC shrink bag (3a), and a PA/EVOH/PE shrink bag (3b). The environmental impact categories

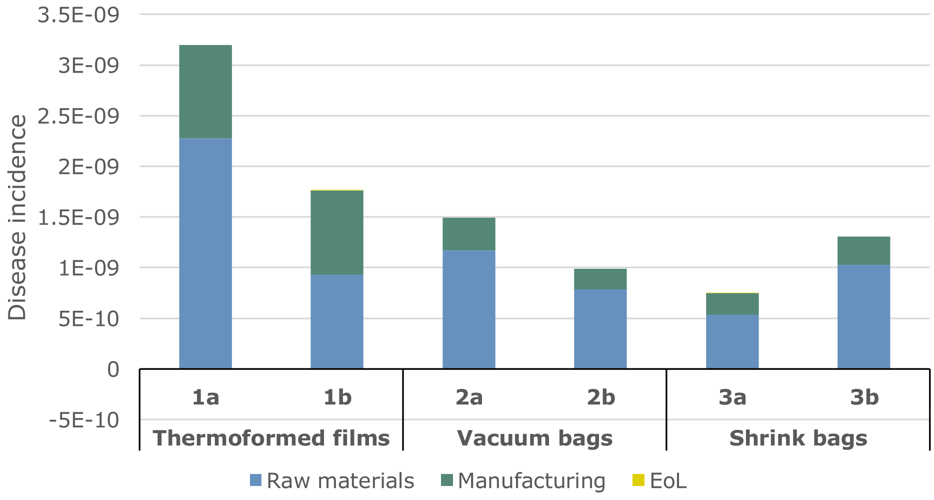

Fig. 4. Respiratory effects results.

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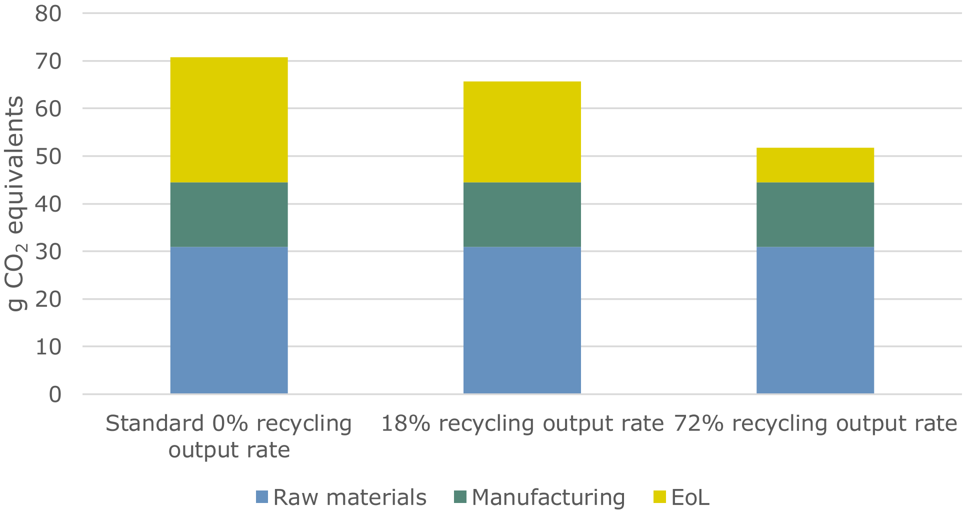

Fig. 5. Climate change results for three recycling scenarios (1b).

climate change, respiratory effects, freshwater eutrophication and fossil resources were analysed over the entire life cycle. When comparing results, one should always keep in mind that the different packaging variants do not only vary in terms of environmental performance, however, there are notable differences regarding barrier properties, mechanical strength, and consumer appeal. Therefore, this study rather aims on highlighting the main drivers of environmental impacts than on identifying the best bacon packaging.

5.1.1. Main drivers for environmental impacts

The environmental impact strongly depends on the weight of the packaging. For the impact catagories climate change, fossil resources and respiratory effects, the results correlate to packaging weight. Although the thermoformed PA/PE film (1a) is only 6% heavier than the thermoformed polyolefin film, the climate change result is 55% higher (Fig. 1). This is due to the fact, that polyamide production causes approximately 4 times more greenhouse gas emissions than PE production. For the recyclable variant 1b, the scenario analysis shows that even if all films (post-consumer waste) were correctly collected, sorted and recycled, the greenhouse gas emissions are only 27% lower compared to complete incineration (Fig. 5). This is due to the low recycling efficiency of only 72% for small films, and the low quality of the recycled material.

The PVdC-containing film 3a performs relatively well compared to the other films due to its low weight of 4.4 g compared to 14 g of variant 1a. Even though toxic dioxins are released during the combustion of PVdC (Yasuhara et al., 2006), modern waste incineration plants filter out dioxin (Hübner et al., 2000). A comparative evaluation of the three toxicity categories (see Appendix) shows that the thin PVdC film performs comparatively well.

The climate change impact category is dominated by raw material production. For all variants containing PA, production of polyamide 6 is either the most important or second most important process. The manufacture of raw materials before processing also dominates the impact category respiratory effects (Fig. 4). Disposal plays a minor role here: due to highly efficient filters in modern waste incineration plants, these emit virtually no particulate matter. Again, PA 6 production is the most important process for all variants containing PA. In the case of fossil resources, raw material production clearly dominates, since the packaging examined - apart from the label - consists exclusively of fossil resources. Polymer production dominates the life cycle impacts of

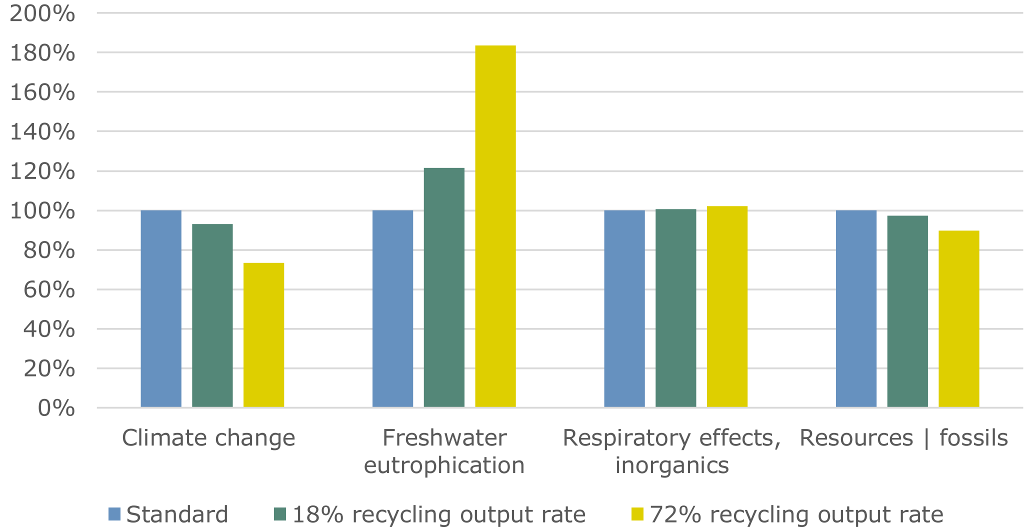

Fig. 6. All impact categories for three recycling scenarios (1b).

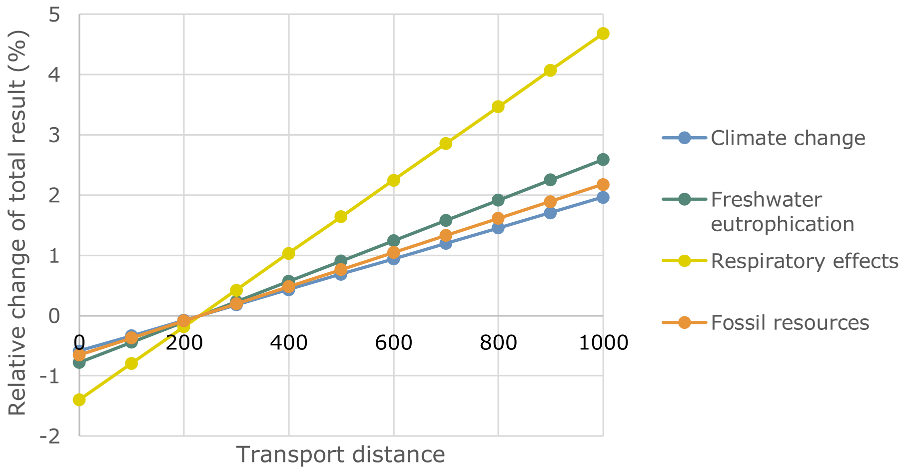

Fig. 7. Sensitivity analysis for transport distance (averaged for all variants).

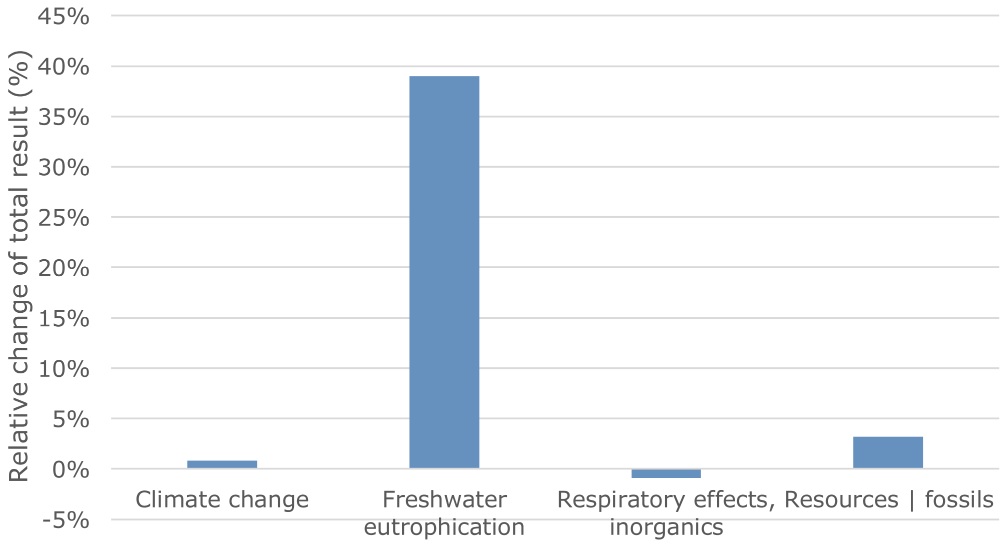

Fig. 8. Sensitivity analysis - LDPE instead of LLDPE (all variants).

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multilayer packaging. This finding is in line with previous studies (Barlow and Morgan, 2013; Maga et al., 2019; Siracusa et al., 2014).

The strong dependence of the value for freshwater eutrophication on the use of electricity is striking. Despite their lower weight, shrink bags perform worse than the vacuum bags due to energy consumption in the shrink tunnel. Since a European electricity mix is used, a proportion of coal-fired electricity is included. The relatively high values are due to the treatment of coal mining overburden, as this involves the release of phosphates into the groundwater (Doka, 2009). High electricity consumption results in high values for freshwater eutrophication whereas waste incineration produces energy and reduces these values. Consequently, the optimistic variant with a great deal of recycling also scores significantly worse in this category than the standard variant, in which the entire packaging is subjected to waste incineration with energy recovery. It should be noted, however, that the ecoinvent data set for coal-based electricity shows a more than 4000 times higher value for freshwater eutrophication than the corresponding GaBi data set (thinkstep AG, 2019).

5.1.2. Sensitivity and scenario analyses

Two recycling scenarios were calculated for variant 1b. A recycling output rate of 18% leads to 7% lower greenhouse gas emissions. In the best case (72% recycling output rate), GHG emissions are reduced by 27% compared to the standard scenario with 0% post-consumer recycling (Fig. 5). The scenario with 18% recycling therefore still performs worse than variants 2a, 2b, 3a and 3b. The optimal recycling scenario (72%) would mean a significant improvement in the result, but this scenario is to date unrealistic for the reasons explained below (see chapter on circularity). The environmental benefits of weight savings, when it comes to PA in particular, clearly exceed the benefits of improved recyclability.

The assumptions regarding transport distance have only a relatively small influence on the results. A change in transport distance affects the repiratory effects result more than the other impact categories. Truck transport contributes to air pollution through fuel combustion, brake and tyre wear, and road abrasion.

LLDPE could be exchanged by LDPE. For the categories climate change and respiratory effects the result changes by slightly less than 1%. The higher deviations for freshwater eutrophication are due to the fact that slightly more electrical energy is used for the production of LDPE (according to ecoinvent 3.6), which leads to the effect discussed above.

The energy consumption for shrinking the films has a relevant

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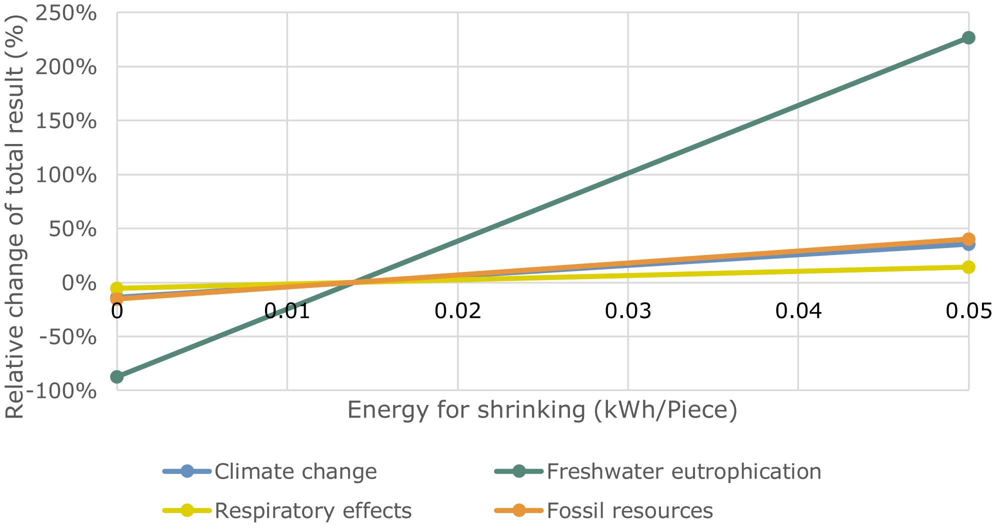

Fig. 9. Sensitivity analysis for heat shrinking – influence of assumptions for energy demand on total result (3a + 3b).

Table 10
Results of the recyclability assessment (RecyClass).

Variant	Class	Short description
1a	F	Not recyclable.
1b	C	Some recyclability issues that affect the quality of final recyclate.
2a	F	Not recyclable.
2b	F	Not recyclable.
3a	F	Not recyclable.
3b	F	Not recyclable.

influence on the overall result. No reliable data could be found in the available literature. The value of 0.0139 kWh is based on assumptions regarding the speed of the shrinking process and the heating energy (see appendix). There are various technologies for the heat shrinking process. The shrink chamber can be heated electrically or by gas. Furthermore, the speed of the packing process varies significantly between different machines. Paricularly with very thin films the energy for shrinking makes up a relevant part of the total environmental impact. A change in energy consumption of 10% for variant 3b leads to a change of 1% for climate change. This means that film manufacturers should use the most energy-efficient shrink machines possible to minimize the environmental impact of these packages.

5.1.3. *Environmental effects, barrier properties and mechanical stability*

The six examined packages differ in their barrier properties and mechanical stability. There are no comparable values for the mechanical properties and the water transmission rate, but for OTR. The two EVOH-containing films 1b and 3b exhibit an excellent oxygen barrier. Version 1a has the highest PA content, and provides excellent mechanical stability, allowing for the packaging of large pieces of hard-edged bacon. This variant also has the highest value for climate change. However, this study does not investigate whether or to what extent these film properties are necessary at all.

5.2. *Circularity*

Circular packaging is made either from recycled material or from biogenic raw materials. It has to be compostable, recyclable or reusable. It should also be produced using renewable energy (Pauer et al., 2019). The Ellen MacArthur Foundation defines three principles of a circular economy: design out waste and pollution, keep materials in use, and regenerate natural systems (Ellen MacArthur Foundation, 2020). Here, we discuss to which extent the examined packaging systems meet these criteria.

5.2.1. *Recyclability issues*

Under current conditions, the polyamide- or PVdC-containing films must be subjected to waste incineration. Only the polyolefin-EVOH film can be recycled, however, the resulting recyclate is not suitable for high-quality use as food packaging. Mixing of PE with EVOH and PP reduces the quality of the recycled material since the hydrophilic EVOH does not mix with the hydrophobic PE. This results in the formation of EVOH beads (Horodytska et al., 2018). Mixing with PP also leads to a reduction in quality (Hubo, 2014). The EVOH content of the packaging should therefore be kept as low as possible. During the recycling process, compatibilizers can also be added to ensure that the different polymers are mixed as evenly as possible (Horodytska et al., 2018). LDPE and LLDPE grades mainly used in the film sector tend to oxidative degradation due to their branching, which leads to further quality loss (Martínez-Romo et al., 2015). Contamination from food residues also impairs recyclability (Hopewell et al., 2009; Horodytska et al., 2018).

Assuming these films were perfectly recyclable, the question of sortability arises (Horodytska et al., 2018). The target fraction for PE films is larger than A4 paper format (210 × 297 mm) for PE einrichment (cyclos-HTP, 2019). Therefore, films smaller than A4 are sorted out by air separation (Kaiser et al., 2018) or manually and sent to energy recovery. The recyclability of these films is reduced not only by the available technology, but recently also by economic conditions.

The recycling of polyamide-containing multilayer films would in principle be possible with novel solvent-based recycling processes (APK, 2020; Fraunhofer IVV, 2020). These processes are not yet economically viable and are not common. However, this may change in the future, which would lead to a re-evaluation of the recyclability of these films.

Extremely thin barrier coatings (<100 nm) providing excellent barrier properties without impairing recyclability could improve recyclability of PE films. Most promising approaches include silicon oxide (Schneider et al., 2009), graphene oxide (Heo et al., 2019), aluminium oxide coatings (Struller et al., 2019), and nanosheet dispersons (Yu et al., 2019). Plastic Recyclers Europe classifies the Ecolam High Plus barrier technology as compatible with recycling. This functional barrier combines EVOH with aluminium metallization, summing up to 1.8% of the total film weight (Plastics Recyclers Europe, 2019b). However, PE films with Ecolam is only classified as conditionally, not as fully recyclable in RecyClass. The COTREP recyclability guidelines for flexible PE recommend the use of thin AlOx, SiOx and COx barrier coatings (elipso, 2016).

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However, the brittleness of these nanocoatings make them prone to fracture during conversion processes like thermoforming and shrinking (Lee et al., 2010; Vähä-Nissi et al., 2012).

5.2.2. *Use of recycled material*

The use of recycled material is restricted by laws pertaining to food quality. Rules for the use of recycled plastic materials intended to come into food contact are laid down in Commission regulation (EC) No 282/2008 (EC, 2015). Clean recycling streams are necessary to ensure recycled plastic that complies with the legal requirements. As of 2020, recycled LDPE and LLDPE have not yet been approved for food contact in accordance to Commission Regulation 282/2008, which might change in the future. Strict regulations do not only apply to layers with direct food contact, but also to outer layers, which are separated from the packaged food by a functional barrier. Monomers or additives may only be used in the manufacture of the layer behind the functional barrier if the migration of this substance is not detectable in food with a detection limit of 0.01 mg/kg (10 ppb). Toxic substances and nanoparticles must under no circumstance be part of multilayer packaging for food (EC, 2016).

Chemical recycling allows the reprocessing of packaging waste into pure, virgin-like monomers (Rahimi and García, 2017). Therefore, chemically recycled plastic is not regulated by 282/2008 in the version of March, 27 2008. In 2019, BASF developed a multilayer cheese packaging made of chemically recycled PA and PE (Connolly, 2019). However, there are serious concerns about the economic and environmental viability of chemical recycling (Bergsma, 2019; Morgan, 2019).

Taken together, these findings suggest that there are still substantial legal, economic and technical barriers for the use of recycled material in multilayer meat packaging.

5.2.3. *Renewable energy sources*

Another relevant indicator for the evaluation of circularity is the use of renewable energy (Korhonen et al., 2018). The remarkable low values of the present results are due to the fact that the use of primary energy sources is taken into account. Raw materials are fossil fuels, and energy for processing is also mainly sourced from fossil sources. In contrast to common perception, however, a higher share of renewables would not automatically make the product more sustainable.

5.2.4. *Biobased and compostable polymers for meat packaging*

It is possible to produce biobased polyethylene (Braskem, 2014) and biobased polyamide (EVONIK, 2020) with the same properties as their fossil-based counterparts. Due to well-established production routes for fossil-based polymers, biobased polymers still remain a niche product.

Researchers undertake great efforts to develop industrially compostable multilayer barrier films. Compostable solutions are possible in principle. Polylactic acid is a brittle material and would have to be modified for flexible applications (Kosior et al., 2006). Intensive research is carried out to improve the barrier properties. The British company The Vacuum Pouch Company Ltd produces industrially compostable vacuum bags for meat without, however, publicly communicating the composition of the film, which is marketed under the name ecopouch (The Vacuum Pouch Company, 2019). Composters often sort out compostable bags alongside with conventional plastic bags since they cannot be easily distinguished (Deutsche Umwelthilfe, 2018).

Biobased and compostable films currently play a subordinate role because conventional plastics perfectly meet the requirements for product protection and consumer appeal. This might change in future due to political pressure, depletion of fossil resources, and progress in materials research.

5.2.5. *Other circularity aspects*

In addition to the aspects of circularity mentioned above, which refers to closed material cycles and renewable energy flows, the Ellen MacArthur Foundation formulates the goal of regenerating natural systems. All the activities involved in the production, processing and disposal of the examined packaging are extractive, not regenerative.

The goal “design out waste and pollution” is partially achieved. Although the use of fossil fuels leads to heavy air pollution, multilayer films are highly efficient systems that provide good product protection at very low weight. According to an IFEU study (Flexible Packaging Europe, 2020), the use of other packaging materials or monomaterials would lead to more material consumption and ultimately to more packaging waste.

5.2.6. *Conclusion for circularity*

These packaging systems do not comply with the requirements of a circular economy as defined by Korhonen et al. (2018). Fossil raw materials are taken from nature, processed and transported using mainly fossil fuels. At the end of their life cycle, they are usually incinerated, which removes this packaging from the biological and industrial cycles. However, the New Plastics Economy Commitment stipulates the reduction of the use of virgin plastics (Ellen MacArthur Foundation, 2018). Resource-efficient multilayer packaging contributes to this reduction, although they are hard to recycle.

5.3. *Food-to-packaging ratio*

This parameter shows the relationship between the environmental impact of the product and the packaging. As expected, the values determined for the packaging examined can be classified as rather high and lie in the typical range for meat packaging (Heller et al., 2019). The environmental impact of primary packaging account for only a few percent (1–4%) of the total environmental impact.

This means that product protection must always have clear priority in the ecodesign of bacon packaging. Improved recyclability or weight reduction only makes sense if there are no higher product losses under any circumstances.

Statements on packaging-related food losses and waste cannot be made, as no empirical study has been carried out. The loss rates for sausages and cured meat given in the literature (Lebersorger and Schneider, 2014) are probably neither representative for prepackaged bacon nor do they show a connection with packaging. However, a small increase in food waste would probably exceed environmental benefits of weight reduction or improved packaging recyclability.

6. Conclusion

6.1. *Main findings*

In conclusion, our findings suggest that the recyclable packaging is not automatically the most environmentally friendly packaging. Lightweight, but non-recyclable mulitlayer vacuum bags or shrink films perform better in terms of environmental impacts than the recyclable PE/EVOH film. Furthermore, our results demonstrate the relatively low environmental significance of packaging compared to the packaged meat. The recyclability assessement of the recyclable PE/EVOH film points to a pressing issue: technical recyclability does not automatically lead to actual recycling. Although some recyclers would accept small polyolefin films for regranulation, these films are usually discarded in the household waste and end in the incinerator.

This study confirms the findings of previous studies, namely that product protection is the clear priority for ecodesign of meat packaging. The environmental benefit of weight reduction is greater than the benefit from improved recyclability. However, progress in material science and recycling technology could enable the production of recyclable, high-performance flexible packaging in the foreseeable future.

We strongly recommend a holistic approach towards the assessment of packaging sustainability, combining LCA with a circularity assessment and a consideration of the environmental impacts of the packaged goods. The present study is the first published study applying this holistic approach on meat packaging. In summary, our results contribute to the ongoing discussion on the Circular Economy by highlighting two important, but often ignored aspects:

1. A more circular product is not always a more resource efficient or sustainable product
2. Technical recyclability does not always lead to actual recycling under the given circumstances

6.2. Limitations

Finally, a number of limitations must be considered. Firstly, the six representative variants do not cover all possible packagings for bacon in block. There is an almost unlimited number of possible combinations in terms of layer thickness and materials used which could further be evaluated. Secondly, the End-of-Life assumptions refer to the situation in Austria. Therefore, the results are applicable for European countries with similar waste management practices, but not for countries landfilling their houshold waste. Thirdly, empirical investigation of the mechanical stability of bacon packaging could also be examined. The relevant parameter would be the puncture resistance since the mechanical stability is very important for product protection. Unfortunately, this parameter is rather rarely stated in the manufacturers' product data sheets and, therefore, was out of the scope of this paper. Finally, this study did not evaluate the potential environmental impacts of novel packaging solutions.

6.3. Recommendations & outlook

Decision makers and packaging designers should bear in mind that improved recyclability does not automatically improve the overall environmental performance of the packaging. There might be trade-offs and conflicts of interest. Cross-sectoral cooperation between packaging industry, waste management industry, recyclers, and regulators is needed to bridge the gap between theoretical recyclability and actual recycling under the given circumstances.

Furthermore, we recommend to scrutinize the potential environmental impacts of novel developments, including monomaterial film packaging with ultra-thin barrier coatings, the use of chemically recycled polymers, and the use of bioplastics. Future research should focus on the development of packaging, which is circular, resource efficient and highly protective. An exclusive focus on recyclability might lead to environmentally undesired outcomes. Therefore, packaging engineers should always take into account the three principles of packaging sustainability: minimization of environmental impacts of the packaging itself, best possible product protection and circularity.

Author statement

Erik Pauer: Conceptualization, Methodology, Investigation, Writing – Original Draft. Manfred Tacker: Supervision. Viktoria Gabriel: Writing – Review & Editing. Victoria Krauter: Writing – Review & Editing

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2020.100001.

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The Influence of Database Selection on Environmental Impact Results. Life Cycle Assessment of Packaging Using GaBi, Ecoinvent 3.6, and the Environmental Footprint Database

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Abstract: This research analyses the differences in impact assessment results depending on the choice of a certain software-database combination. Six packaging systems were modelled in three software-database combinations (GaBi database in GaBi software, ecoinvent 3.6 database in openLCA, Environmental Footprint database in openLCA). The chosen Life Cycle Impact Assessment (LCIA) method is EF 2.0. Differences and errors in the implementation of the LCIA method are a possible source of deviations. We compared the published characterisation factors with the factors implemented in the software-database combinations. While results for the climate change category are similar between the different databases, this is not the case for the other impact categories. In most cases, the use of the ecoinvent 3.6 database leads to higher results compared to GaBi. This is partly due to the fact, that ecoinvent datasets often include more background processes than the corresponding GaBi datasets. We found striking discrepancies in LCIA implementation, including the lack of regionalisation for water use in ecoinvent. A meaningful communication of LCIA results requires an excellent knowledge of the analysed product system, as well as of database quality issues and LCIA methodology. We fully acknowledge the constant efforts of database providers to improve their databases.

Keywords: packaging; life cycle assessment; databases; life cycle impact assessment; ecoinvent; GaBi; environmental footprint database

1. Introduction

1.1. Background

Packaging plays a central role in our economy. Despite its importance, it has come under scrutiny due to its contribution to the ever increasing amounts of solid waste [1]. Growing public pressure is leading to major efforts to reduce the negative environmental impact of packaging. To understand these impacts, Life Cycle Assessments (LCA) are carried out. The results of packaging LCAs can have far-reaching consequences. For example, an LCA carried out by the German Federal Environment Agency [2] served as the basis for the introduction of the return deposit system for disposable beverage packaging in Germany. Since composite beverage cartons had particularly low environmental impacts in this study, they were exempted from the mandatory deposit [3]. Several companies use LCA as a basis for decision-making [4]. Due to the high relevance, the question arises as to how reliable and comparable the results are in general. This paper deals with the question of how the choice of a certain Life Cycle Inventory (LCI) database influences LCA results for packaging.

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1.2. LCA Tools

Commercially available LCA tools consist of several elements. Life Cycle Inventory databases contain datasets that characterise different processes. Each process consists of input flows (e.g., resources) and output flows (e.g., emissions). In addition, each dataset should include sufficient documentation [5]. These databases are tightly integrated with an application software, which allows for user-friendly access to the datasets. Users can combine datasets to complex models. LCA tools include various Life Cycle Impact Assessment (LCIA) methods facilitating the calculation of environmental impacts. An LCIA method is essentially a list of characterisation factors for the input/output flows. These factors translate inventory results (e.g., emissions) into environmental impact results. Taken together, an LCA tool consists of three distinct elements:

- Embedded LCI database
- Application software
- LCIA methods

The LCI database and the LCIA methods have to be seamlessly integrated with the software. Moreover, the characterisation factors of the LCIA methods must be mapped to the flows of the datasets. In this work, we refer to these tools as software-database combinations.

1.3. Relevant Influencing Factors for LCA Results

Several factors influence the reliability of the results. In addition to the quality of the primary data and the definition of the system boundaries, methodological aspects also have a major influence on the results. Various allocation methods lead to very different results [6]. Moreover, there are often different LCIA methods for the same impact category. For example, there are different metrics for the category of climate change, which differ with regard to the time period under consideration (20, 100, or 500 years), or with regard to the indicator (increase in radiative forcing or increase in temperature) [7].

The choice of secondary data also has a major influence [8]. Various providers offer secondary data in the form of LCI databases. There are different approaches to process modelling. Different system boundaries, assumptions, and the spatial and temporal validity of the datasets lead to different results depending on which database is used. Among the most widely used LCI databases are the ecoinvent database [9] and the GaBi database [10].

1.4. Literature Review

A number of researchers have reported large differences in results for the same product depending on the software-database combination used.

Kalverkamp et al. [8] modelled the life cycles of an electric car and a car with a combustion engine using both GaBi and the ecoinvent database. LCIA was carried out using the "ReCiPe" method. While the differences for the categories climate change, fossil resources, particulate matter, and acidification were relatively low, there were large variations for other categories (e.g., ozone depletion and water consumption). However, no clear trend could be shown, since in some cases the ecoinvent results were higher than the GaBi results, and vice versa. The authors recommend modelling the product systems with different databases for important decisions.

Emami et al. [11] carried out an LCA for different buildings. They modelled the systems with both GaBi and ecoinvent databases. While the climate change results were comparable, the results for other impact categories varied greatly, with the GaBi results almost always substantially lower than with the ecoinvent results. As a possible cause, the authors discuss the so-called cut-off error, which is caused by the fact that it is impossible to map all precursor processes. A system boundary must be drawn somewhere, and this differs from database to database.

Herrmann et al. [12] compared the results for different agricultural products modelled both with GaBi and ecoinvent. Here too, very large differences were found. This is due on the one hand to the life cycle inventory, and on the other hand to the implementation of the impact assessment method in

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the software. The discrepancies are so great that they could lead to the fact that—depending on the database used—different conclusions could be drawn from life cycle assessments of the same product.

Ciroth [13] carried out a comparative analysis of a light bulb. He used GaBi and ecoinvent, both integrated in the software openLCA. Here, GaBi often showed higher results than ecoinvent. The author attributes the variations to three causes: (i) differences in the Life Cycle Inventory, (ii) that the selected dataset does not adequately represent the system under investigation, and (iii) poor implementation of the impact assessment method.

Speck et al. [14] have shown that even if the same database is used and the same Life Cycle Impact Assessment (LCIA) method is applied, different results are obtained if different LCA software is used. The reason for this is the different implementation of the LCIA methods in the respective software.

Taken together, the published findings suggest that LCIA results other than climate change differ largely depending on the used software-database combination. Reasons are manifold, and communication of LCIA results without profound understanding of the database structure and the used LCIA method is highly problematic.

1.5. *Efforts towards Standardisation*

Although ISO 14040/44 [15] standardise the conduct of LCA, there is a certain methodological diversity. Various calculation methods lead to different results for the same product. Therefore, a comparison between products is only permissible if the LCAs were calculated using the same calculation method and the same database. The fundamental problem has been known for a long time. As a result, the European Commission launched the initiative for the development of the Product Environmental Footprint (PEF), which aims at standardisation [16,17]. The desired standardisation includes not only the LCIA methods and the End-of-Life (EoL) allocation formula, but also the datasets. Comparability can only be achieved if the same database is always used. Therefore, the European Commission released a database containing secondary data recommended for PEF studies. This database, henceforth called EF database, is available for openLCA [18] and GaBi software.

1.6. *Aim and Research Question*

This paper is the first study to systematically investigate how the choice of a certain database influences the LCA results of packaging. Due to the great interest from industry, this question is of high relevance. In addition, we investigated whether the selected LCIA method has been correctly implemented, and what influence an incorrect implementation of the LCIA method has.

In this study, the environmental impacts of different packaging systems over the entire life cycle are assessed with three software-database combinations.

It is not the aim of this study to create as accurate models of packaging systems as possible. It is also not the aim to compare different packaging systems, nor does it deal with uncertainty of the results. The results refer to the most recent databases in July 2020. At the time of publication, improved versions of the used databases have been released. Therefore, the authors recommend focussing on general conclusions rather than on specific numbers, which become—sooner or later—outdated.

2. Materials and Methods

This section is divided into three sub-sections. First, the systems under investigation are presented, including the assumptions regarding transport and disposal. Then the databases, software, and LCIA methods used are described. Finally, the calculation method, i.e., allocations, system boundaries, functional unit, and selection of the most relevant impact categories are presented. Moreover, we introduce an approach to analyse the reasons for the observed differences.

2.1. *Investigated Systems*

Different packaging systems are analysed over the entire life cycle. The aim is to model average European packaging that is as close to real-life conditions as possible. The information on mass and

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composition of the packaging is based on Dinkel et al. [19], except for the plastic bag and the corrugated cardboard box. In these cases, assumptions had to be made. The sources of the assumed recycled contents and recycling rates are given in the table caption (Table 1). These are simplified systems as the focus is on comparing the different databases, therefore packaging aids such as closures, labels, or secondary packaging were not considered.

Table 1. Properties of the analysed packaging systems.

System	Mass (g)	Material	Recycled Content	Recycling Rate
PET bottle (0.5 L)	21.89 [19]	Polyethylene terephthalate (PET)	0% [20]	42% [20]
Plastic bag	5	Low density polyethylene (LDPE)	0% [20]	0% [20]
Glass bottle, disposable (0.5 L)	260 [19]	Glass (unspecified colour)	52% [20,21]	66% [20]
Aluminium can (0.5 L)	15.8 [19]	Aluminium	0% [20]	69% [20]
Tinplated steel can (0.5 L)	31.3 [19]	Tinplated steel	58% [22]	74% [20]
Corrugated box	300	Corrugated board	88% [20,23]	75% [20]

Information on mass is based on Dinkel et al. [19] and on own assumptions. Data on recycled content and recycling rates are based on Annex C of the PEF Guidance [20], European Container Glass Federation FEVE [21], Association of European Producers of steel for packaging APEAL [22] and European Federation of Corrugated Board Manufacturers FEFCO [23].

In addition to the packaging systems, the process “Electrical energy (consumption mix)” is also compared in detail.

The following assumptions for the transport scenario refer to the Product Environmental Footprint Category Rules (PEFCR) Guidance document [17] and apply to all packaging systems examined:

- 230 km truck
- 280 km railway
- 360 km ship

For thermal and electrical energy, the average European consumption mix was assumed in each case. The recycling rates are given in the descriptions of the individual packaging systems. For non-recycled packaging waste, it is assumed that 50% is thermally recovered and 50% is landfilled [20].

2.2. Databases, Software, and LCIA Methods

The calculations were carried out using GaBi, ecoinvent 3.6, and the Environmental Footprint (EF) database published by openLCA [24]. For modelling, the software GaBi was used for the GaBi database, and the software openLCA for the ecoinvent and EF database. The impact assessment was carried out using the EF 2.0 method proposed in the PEFCR guidance document [17,25]. This is a set of recommended methods for evaluating 16 different impact categories. The name of this method differs slightly in the different databases. Table 2 provides an overview:

Table 2. Software-database combinations and naming of the Life Cycle Impact Assessment (LCIA) method EF 2.0. ILCD stands for International Reference Life Cycle Data System.

Database	Software	LCIA Method (Name)
GaBi	GaBi ts (Version 9.5.2.49)	Environmental Footprint (EF) 2.0
ecoinvent 3.6 (cut-off)	openLCA 1.9.0	ILCD 2.0 2018 midpoint
Environmental Footprint secondary data for openLCA	openLCA 1.9.0	Environmental Footprint (Mid-point indicator)

2.3. Method of Calculation

2.3.1. System Boundaries

The present analysis refers to the entire life cycle of packaging and includes raw material production, processing, transport, and disposal. The most current inventory data was used, and waste statistics refer to the latest years. The aim is to present a plausible European scenario for the period from 2015 to 2020.

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2.3.2. Allocation

The End-of-Life allocation was carried out using the Circular Footprint Formula (CFF) as far as possible. This method is recommended by the European Commission [17] and allows for a fair calculation of credits for the use of recycled material and for recyclability at the end of life. Some datasets, such as the GaBi packaging glass dataset or the ecoinvent steel dataset, already contain a certain recycled content. Consequently, the life cycle of certain packaging systems had to be modelled according to the preset allocation method. As shown in Table 3, it was not possible to consistently apply the Circular Footprint Formula in all cases. This important limitation is discussed in more detail in section four.

Table 3. Applied allocation procedures.

Database	PET Bottle	Plastic Bag	Glass Bottle	Aluminium Can	Tinplated Steel Can	Corrugated Box
GaBi	CFF	CFF	Cut-off	CFF	Worldsteel (value of scrap) [26]	Cut-off
ecoinvent 3.6	CFF	CFF	Cut-off	CFF	Cut-off	Cut-off
EF DB	CFF	CFF	Cut-off	CFF	CFF	CFF

2.3.3. Impact Assessment Method

The 16 environmental impact categories as recommended in the PEF guidance [17] are calculated. The methodology refers to version EF 2.0. Although at the time of this study, a more recent version (EF 3.0) already existed, since this impact category method set was only available for GaBi, version EF 2.0 was used for consistency reasons. The names of the impact categories differ slightly between the various databases, so the nomenclature of the PEFCR guidance document [17] is uniformly used in this study.

2.3.4. Normalisation and Weighting

To select the most important impact categories, we carried out a normalisation and weighting of the results with the factors recommended by the European Commission [25]. For every model (e.g., PET bottle in GaBi, corrugated box in ecoinvent, etc.), the three most important impact categories were determined.

2.3.5. Presentation of the Results

Since the aim of this paper is to show the relative differences in the results, they are presented in percentages, with the Gabi results being arbitrarily set as 100%. The most important impact categories are presented. Since not only the absolute results differ in different databases, but also the ranking of the most important categories, more than three impact categories are usually presented. For example, if the GaBi calculation shows climate change, fossil resources, and water use as the three most important categories, and the ecoinvent calculation shows climate change, fossil resources, and respiratory diseases, then four impact categories are shown, namely climate change, fossil resources, respiratory diseases, and water use.

2.3.6. Analysis of Differences

If the results differ by greater than 50%, the most important contributing flows are examined in more detail. Due to the high relevance of the impact category "climate change," deviations greater than 20% are analysed. This involves analysing which processes lead to the respective emissions and how these processes differ between the various databases.

In addition, an analysis of the impact assessment method was carried out. Since Speck et al. [27] have pointed out that one and the same impact assessment method can be implemented differently and in some cases incorrectly in different software-database combinations, the characterisation factors of the most important flows of the individual impact categories [28] were systematically compared. For this purpose, the characterisation factors in the individual software-database combinations are

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compared with the original factors provided by the European Commission for the EF 2.0 method [25]. The most important flows are defined as those flows which together account for at least 80% of the environmental impact. Any deviations are described in Section 3.3.

3. Results

In this section, we present the relative differences between the results, and discuss possible reasons. Furthermore, deviations of the characterisation factors—as implemented in the analysed software-database combinations—from the official EF 2.0 characterisation factors are also discussed.

3.1. Differences in the Results

3.1.1. PET Bottle

In the EF database, an aggregated dataset for bottle production was used. This dataset covers the PET granulate production and the bottle processing. In GaBi and ecoinvent, datasets for PET granulate were used, and bottle manufacturing was modelled separately. Figure 1 shows the variations in the results for the PET bottle.

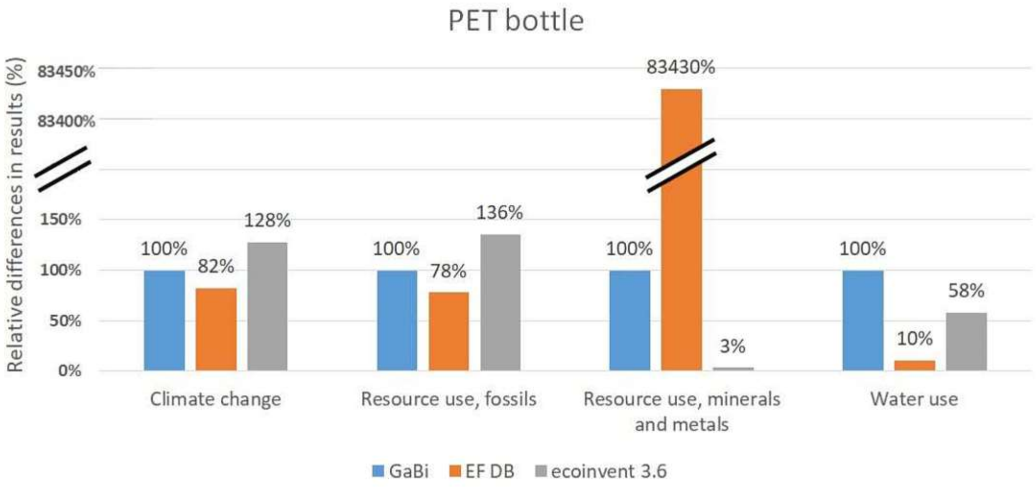

Figure 1. Relative differences in results for the main impact categories for the polyethylene terephthalate (PET) bottle.

Climate change: The datasets for the raw material "PET, bottle grade" are in all three databases based on the PET ecoprofile [29]. While the results for the raw material in GaBi and in the EF database are very similar to the original ecoprofile, this is not the case for ecoinvent 3.6, where greenhouse gas emissions are substantially higher. The fact that the overall results for the EF database is lower than for GaBi is partly due to assumptions concerning energy consumption during processing. Furthermore, the production of bottles is an energy-intensive process. Therefore, environmental impacts for electrical energy (see Section 3.1.7) also lead to a higher result for ecoinvent 3.6.

Resource use, minerals, and metals: The strikingly high results are due to the fact that the EF dataset for PET bottles assumes substantially higher antimony consumption compared to the other databases. The low result for ecoinvent 3.6 is caused by the lack of characterisation factors for antimony and other elements in the impact assessment method (see also Section 3.3).

Water use: Remarkable low results for the EF database are caused by the fact that with ecoinvent 3.6 and GaBi, considerably more process water is consumed in the processing of the plastic than for the EF database.

3.1.2. Plastic Bag

The following graph (Figure 2) shows the differences in the results for the LDPE plastic bag.

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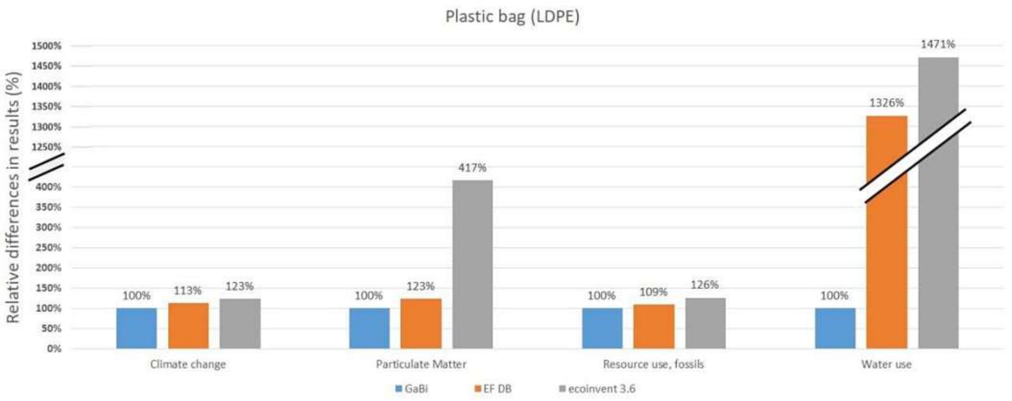

Figure 2. Relative differences in results for the main impact categories for the low density polyethylene (LDPE) plastic bag.

Climate change: The higher results in ecoinvent 3.6 stem from higher CO_2 emissions for the extrusion process.

Particulate matter: The higher values in ecoinvent 3.6 mainly arise from discrepancies in the upstream chain. For ethylene production using steam cracking, ecoinvent 3.6 assumes considerably higher emissions of SO_2 and PM2.5.

Water use: Higher results for EF database are primarily due to water losses during the extraction of cooling water from rivers. In the GaBi database, there are anomalous negative results in this impact category for LDPE production.

3.1.3. Glass Bottle (Disposable, 0.5 L)

The GaBi dataset is an aggregated process, including production, transport, and disposal of container glass. As not all assumptions for this process are transparent, it was not possible to model the exact same system with the ecoinvent 3.6 or EF database. Figure 3 shows the differences in the results for the disposable glass bottle.

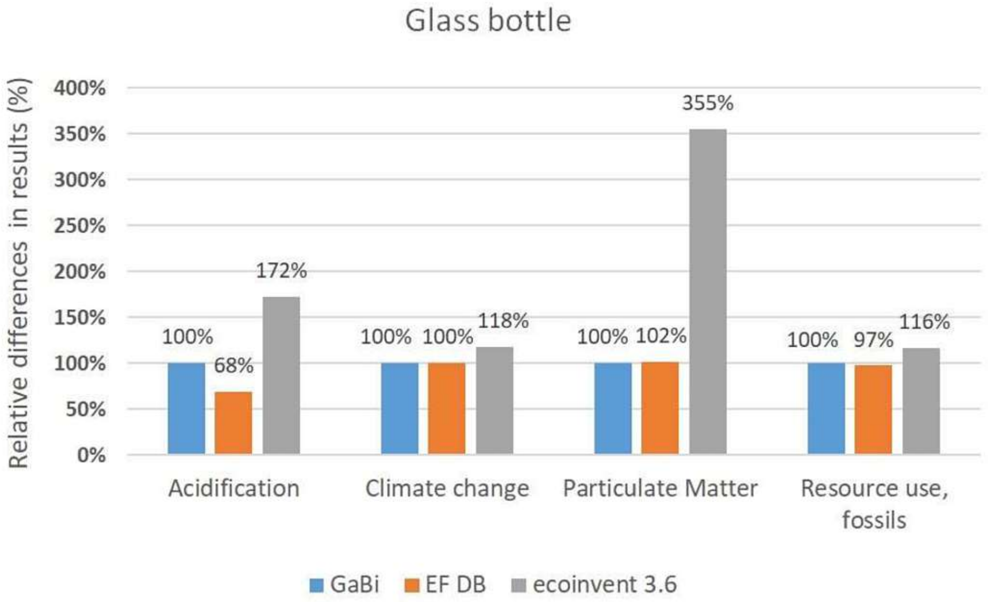

Figure 3. Relative differences in results for the main impact categories.

Acidification and Particulate matter: Substantially higher NOx and PM2.5 emissions in the ecoinvent 3.6 datasets for glass production lead to higher results for the impact categories acidification and particulate matter.

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3.1.4. Aluminium Can (0.5 L)

Can making was modelled according to da Silva et al. [30]. Figure 4 shows the differences in the results for the aluminium can.

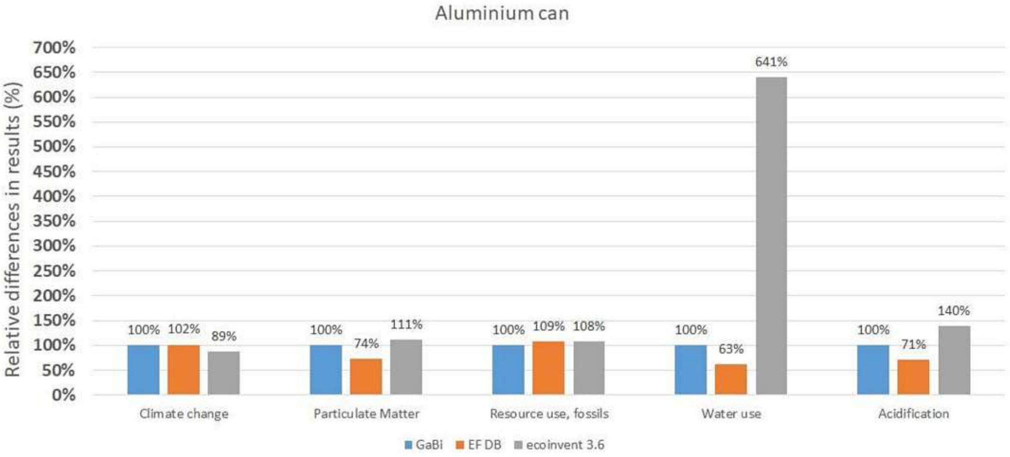

Figure 4. Relative differences in results for the main impact categories.

Water use: Substantially higher results for ecoinvent 3.6 are due to the fact that a great deal of water is used in aluminium processing. Norway plays a major role in the European aluminium industry. In the ecoinvent impact assessment method "ILCD 2.0 2018," there are no regionalised characterisation factors for water; therefore, the global characterisation factor of 42.85 m^3 world-equivalents/m^3 is used. As the characterisation factor for water from Norway is lower (0.634 m^3 world—equivalents/m^3) than the global one, the GaBi result is also much lower. That means that the amount of consumed water is similar in GaBi and in ecoinvent; however, this value is multiplied with an unrealistically high characterization factor in ecoinvent.

3.1.5. Tinplate Can (0.5 L)

In the case of the tinplate can, different allocation procedures contribute to deviations in the impact results (see Section 2.3.2). Figure 5 shows the differences in the results for the tinplate can.

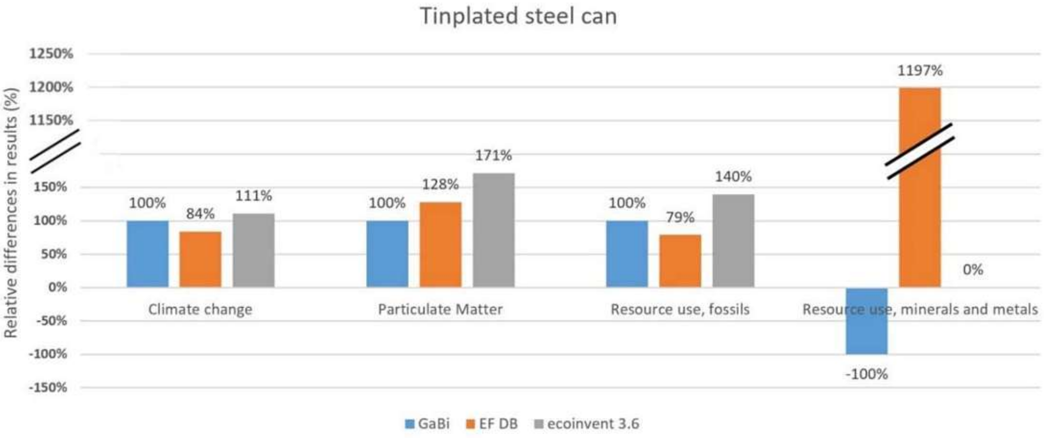

Figure 5. Relative differences in results for the main impact categories.

Particulate matter: The higher results for ecoinvent 3.6 arise from the upstream chain of steel production. High emissions from coal mining are assumed here. These emissions stem from the coal that is burned for energy generation near the mine.

Resource use, minerals, and metals: The negative value for GaBi is due to the fact that the credit calculated with the "Value of scrap" dataset is higher than the value for resource consumption in

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steel production. While the credit for iron is expectedly lower than the iron consumed in production, the credit for silver, chromium, lead, magnesium, silicone, and zinc is higher than the resources consumed in production. The high value for EF database comes from copper consumption. The low value for ecoinvent can be partly explained by the lack of characterisation factors (see Section 3.3.2).

3.1.6. Corrugated Box

Figure 6 shows the differences in the results for the corrugated box.

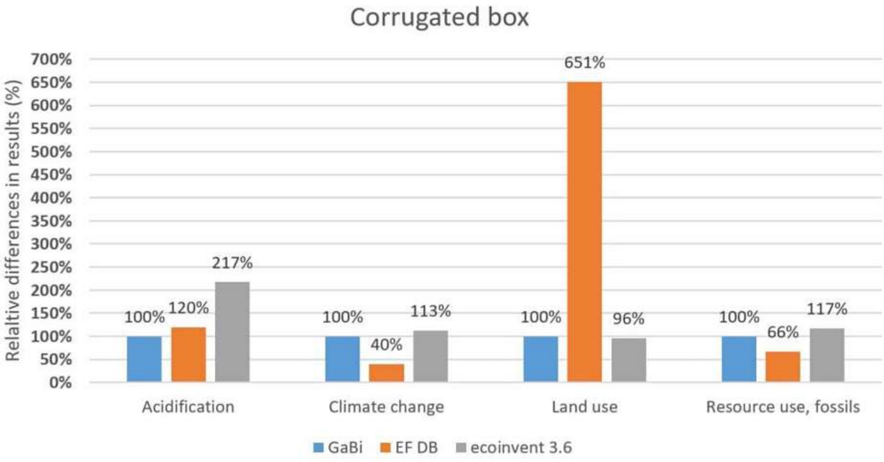

Figure 6. Relative differences in results for the main impact categories.

Climate change: All corrugated datasets in the three databases are based on the FEFCO study [23]. The low value for climate change in the EF database is therefore all the more noticeable. This dataset contains an unusual negative flow for biogenic methane.

Acidification: The ecoinvent 3.6 results are substantially higher due to higher SO_2 and NOx emissions during the production of kraftliner (linerboard).

Land use: High values for the EF database compared to GaBi are due to the fact that a higher land consumption is assumed (e.g., land occupation "forest used": 1.4 m^2 *a for EF database; 0.264 m^2 *a for GaBi). In addition, GaBi uses regionalised flows, whereas EF database comprises global flows with high characterisation factors.

3.1.7. Electricity, EU Consumption Mix

Figure 7 shows the differences in the results for electricity.

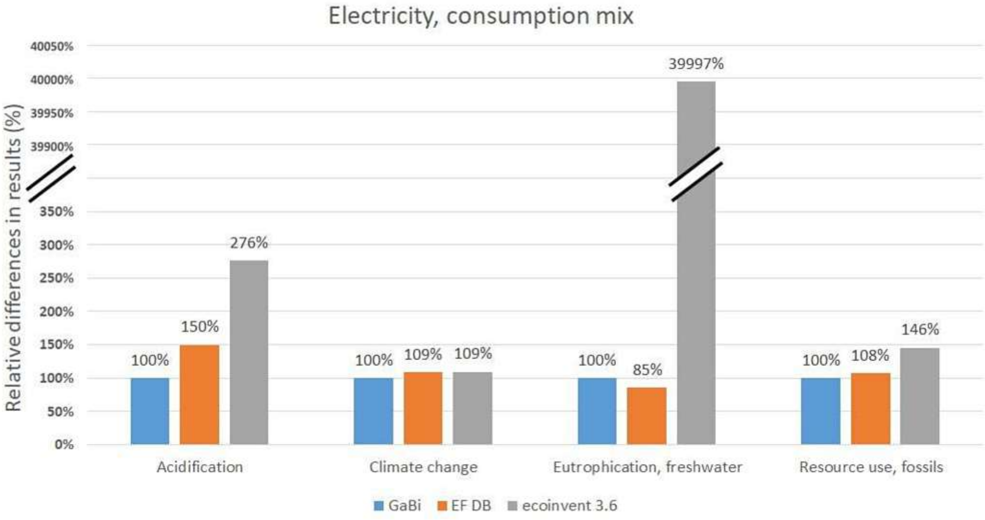

Figure 7. Relative differences in results for the main impact categories.

Acidification: Substantially higher SO_2 emissions from coal-fired power plant compared to the other databases lead to higher acidification results for ecoinvent 3.6.

Freshwater eutrophication: The strikingly high result for ecoinvent 3.6 is due to the treatment of coal mining overburden, as this involves the release of phosphates into the groundwater [31].

3.2. Further Differences in Impact Category Results

An analysis of the results for all impact categories for the seven systems investigated (six packaging systems and electrical energy) has shown that for the following impact categories the ecoinvent 3.6 results are always higher than the GaBi results:

- Acidification
- Eutrophication, freshwater
- Human toxicity, cancer
- Ionising radiation, human health
- Ozone depletion
- Photochemical ozone formation, human health
- Resource use, fossil

Results for the sixteen PEF impact categories were calculated for each product system. On average, almost 14 (exactly 13.86) impact category results from ecoinvent are higher than the corresponding results for GaBi per product system.

3.3. Differences in the Characterisation Factors

The characterisation factors of the most important flows were compared with the original EF 2.0 method [25]. In addition, the extent to which regionalisation is present in the characterisation factors and whether this regionalisation is implemented in the different software packages was verified.

3.3.1. Regionalisation

Table 4 gives an overview of all impact categories for which regionalised characterisation factors exist in the original and shows the implementation in the different software packages.

Table 4. Regionalisation of characterisation factors. n.a. = not available; ok = as implemented in the original.

Impact Category	EF 2.0 (GaBi)	Environmental Footprint (EF Database)	ILCD 2.0 2018 (Ecoinvent)
Acidification	n.a.	Regionalised characterisation factors available in the implemented LCIA method, but no regionalised flows in the EF database	n.a.
Eutrophication, terrestrial	n.a.	Regionalised characterisation factors available in the implemented LCIA method, but no regionalised flows in the EF database	n.a.
Land use	ok	Regionalised characterisation factors available in the implemented LCIA method, but no regionalised flows in the EF database	n.a.
Water use	ok	ok	n.a.

In GaBi, there are both regionalised flows and regionalised characterisation factors for water and land use. In the impact assessment method for the EF database, there are regionalised characterisation factors for acidification, eutrophication, and land use; however, the database lacks the regionalised flows. The method "ILCD 2.0 2018" does not include any regionalised characterisation factors.

None of the analysed software-database combinations provides regionalised flows for acidification and terrestrial eutrophication. This is remarkable due to the potentially large discrepancies in results.

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For acidification the characterisation factor for "Sulfur dioxide—Greece" is 0.012, while the factor for "Sulfur dioxide—Sweden" is 1.993. Soil sensitivity to acidification differs largely between regions, and should therefore be considered in impact assessment [32].

3.3.2. Characterisation Factors

Any differences between the characterisation factors are described here. The issue of regionalisation will not be dealt with separately.

- Climate change: The characterisation factor for fossil methane is 36.8 in the original EF2.0 method. In "ILCD 2.0 2018" it is 36.75.
- Ecotoxicity: In GaBi and in the ecoinvent method "ILCD 2.0 2018," the characterisation factors for "estradiol to water" are missing. The reason for the lacking estradiol characterisation factor in GaBi is the lack of contributing processes in the database. In ecoinvent, the characterisation factor for cyfluthrin is also absent.
- Resource use, minerals, and metals: In the ecoinvent method "ILCD 2.0 2018," the characterisation factors for germanium and antimony are missing. However, this error was redressed by ecoinvent with the release of version 3.7.

4. Discussion

4.1. Main Findings

The present analysis discloses large differences between the analysed software-database combinations. While the results for climate change are generally quite similar, this is not the case for other impact categories. It is noticeable that the results for ecoinvent are in most cases substantially higher than for GaBi. Results for the EF database in openLCA are occasionally higher and occasionally lower than for GaBi. The reason is that EF database is based on data from various providers, including Sphera (formerly thinkstep) and ecoinvent. Variations are caused by differing system boundaries and on occasion by insufficient implementation of the assessment method into the examined software-database combinations.

4.2. Possible Reasons for the Higher Values in Ecoinvent

It is noticeable that the results of the impact assessments from ecoinvent 3.6 are commonly higher than GaBi results. For example, an evaluation of the generation of 1 kWh of electricity from nuclear energy (Germany) shows that the result for "ionising radiation" in ecoinvent is twice as high as in GaBi. The high value at ecoinvent is mainly due to the dumping of overburden from the mining of uranium ore. Similarly, the rather high values for freshwater eutrophication in coal-fired power plants are due to the dumping of coal tailings. Since the GaBi datasets are aggregated datasets, it could not be determined whether these processes are contained in GaBi at all. A comparison of transport processes also shows higher results for ecoinvent in the category climate change. The documentation of the datasets clearly shows that ecoinvent also includes road maintenance and vehicle wear, which is not the case with GaBi. Only the direct emissions of the vehicle and burdens from fuel production are included here.

From this, we conclude that in some cases, different system boundaries lead to higher results. In many cases, the ecoinvent datasets contain considerably more background processes (e.g., wear and tear of infrastructure, maintenance work, etc.) than GaBi.

One reason for the higher values in the water use category is the use of the global characterisation factor for water, which leads to inflated results if the water was consumed in regions without water shortage.

However, since no complete analysis of all GaBi and ecoinvent datasets has been carried out, generalisations should be treated with caution.

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4.3. Quality Issues

Despite the constant improvements and updates, errors were found in all three databases. These errors exist on the level of the Life Cycle Inventory and in the implementation of the LCIA methods. For example, the negative flow for biogenic methane in the EF dataset for corrugated board leads to dramatically lower values in climate change compared to GaBi or ecoinvent 3.6. The lack of characterisation factors for elements such as antimony in ecoinvent leads to very low values in the impact category "resources, minerals, and metals." The lack of regionalisation of flows and characterisation factors severely limits the significance of the results for land use, water use, acidification, and terrestrial eutrophication.

4.4. Different Allocations

The End-of-Life allocation method cannot always be freely chosen by the LCA practitioner. It also depends on the database used. This is particularly important when aggregated datasets are available and materials with recycled content are considered. For example, in GaBi, the steel sheet dataset was calculated using the worldsteel allocation method, but the glass dataset was calculated using the cut-off method.

4.5. Limitations

For several reasons, full comparability is difficult to achieve. For example, it was not always possible to use the same allocation method because some raw material datasets (steel, glass, paper) already contain a certain amount of recycled material. Consequently, the same allocation method has to be applied for the disposal of packaging. Numerous authors have pointed out that various allocation methods produce large differences in the results [6].

Such a study can only be a snapshot. At the time of publication, for example, a more recent version of ecoinvent was published (3.7). Updated datasets on electricity mix, metals, paper, and recycling were released. Furthermore, the missing characterisation factors for "resource use, minerals, and metals" were added. The method was renamed from "ILCD 2.0 2018" to "EF 2.0" [33]. The GaBi database and software is also regularly updated and improved. Despite these important limitations, some general conclusions can be drawn from this study.

5. Conclusions

The results of this study clearly show that a meaningful evaluation and interpretation of results requires a solid background knowledge. This expert knowledge should include both an understanding of the system under study and the LCIA methods used. Despite the constant improvements, there are still errors in the databases. Incorrect flows, wrong or absent characterisation factors can lead to erroneous conclusions.

These findings also have consequences for the selection of the main impact categories. If these are selected using purely quantitative methods such as normalisation and weighting, there is a risk that the importance of some impact categories may be under or overestimated.

Climate change is always included in the most important categories, but often also particulate matter and acidification. Water and land use are important categories, but implementation of the method is still inadequate in some cases. The impact categories "resource use, fossils" and "resource use, mineral, and metals" are problematic for several reasons. The consumption of fossil resources correlates strongly with greenhouse gas emissions [34], so this indicator does not provide any additional information. The impact category "resource use, minerals, and metals" is also associated with large uncertainties [35]. This is shown by the large discrepancies in the results for this impact category for the PET bottle and the tinplate can. Moreover, it is questionable whether depletion of fossils, minerals, or metals is an environmental concern at all [36].

One of the most important tasks of an LCA practitioner is to be able to assess the quality of the data and the relevance of the impact categories. Overall, our findings suggest that for a meaningful packaging life cycle assessment, good quality of secondary data and reliability of the LCIA methods are absolute prerequisites. Our findings underline the importance of modelling product systems with different databases for important decisions, as recommended by Kalverkamp et al. [8].

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Abstract

Growing awareness for environmental issues and stricter legislation increases the pressure on producers to address these issues. In particular, packaging is under scrutiny, because it is perceived as a major contributor to waste streams and resulting environmental problems.

This review provides an overview of the existing tools used to assess the environmental impacts of packaging. While a full life cycle assessment (LCA) is an appropriate tool to assess the impacts of a well-established product, simplified LCA allows a quick and less detailed assessment during, for example, the design phase of a certain product. Furthermore, scorecards are capable of addressing pre-selected environmental aspects of packaging. Whenever applying simplified LCA or scorecards, the inevitable trade-off between accuracy and user-friendliness has to be considered. Nevertheless, a careful selection of the indicators to be assessed and a good understanding of the packaging system allow results to be meaningful even with these simplified tools.

Keywords

Packaging, Life Cycle Assessment, Streamlined Life Cycle Assessment, Simplified Life Cycle Assessment, Ecodesign Tools, Scorecards, LCA, SLCA

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1. *Introduction*

Methods to assess the environmental impact of packaging have gained increasing interest over the last decades. In particular, packaging is an often-studied Life Cycle Assessment (LCA) topic (Franklin et al., 1974; Ayres, 1995; Falkenstein Wellenreuther & Detzel, 2010, Detzel & Mönckert, 2009; Gasol, Farreny, Gabarrell & Rieradevall, 2008; Belboom, Renzoni, Verjans, Léonard & Germain, 2011; Humbert, 2009; Odabasi, 2016; Verghese, Horne & Carre, 2010). The first packaging LCA study was undertaken in the late 1960s and was commissioned by Coca Cola (Franklin & Hunt, 1996). Procter & Gamble assessed the environmental impacts of their laundry detergent packaging in the early 1990s (Verghese, Lewis, Lockrey & Williams, 2013, p. 174-175). The holistic life-cycle approach provides several advantages, because it avoids the risk of shifting environmental burdens from one life cycle stage to another by evaluating all life cycle stages. By assessing several different environmental impact categories, the risk of shifting the burden from one environmental topic to another can be minimized (Flanigan, Frischknecht & Montalbo, 2013). LCA has become an integral part of the industrial decision-making process (Dorn, 2016). The increased use of LCA has boosted demand for streamlined and tailor-made LCA-based-tools (The Consumer Goods Forum, 2011). This trend derives from the fact that for many years packaging has been center stage in political and consumer campaigns to address perceptions of unsustainable consumerism in Western society (Verghese, Lewis & Fitzpatrick, 2012). Ocean littering for example has become a major environmental concern, and packaging is an important contributor to marine plastic debris (Lavers & Bond, 2017; Jambeck et al., 2015; Ingrao, Gigli & Siracusa, 2017; United Nations Environment Programme (UNEP), 2016). On the other hand, intelligent packaging can contribute to product sustainability since it prevents product damage. Particularly food loss can be significantly reduced by suitable packaging (Gutierrez, Meleddu & Piga, 2017; Verghese

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et al., 2013). Optimized packaging often provides environmental advantages. The reason is that the benefits of prevented food waste are often higher than the environmental impacts of production or optimization of the packaging involved (denkstatt, 2014). This example makes clear that for a good understanding of the environmental impacts the packaging should not be analyzed separately from the contained product to avoid burden shifting (Grant, Barichello & Fitzpatrick, 2015). A reduction of packaging material, which would lead to increased product damage, would be counterproductive (denkstatt, 2014). The influence of packaging attributes on recycling and food waste behavior should also be taken into account (Wikström, Williams & Venkatesh, 2016). This publication, nevertheless, focuses on the assessment of environmental impacts of packaging alone, since packaging-assessment is the first step of the overall assessment process.

The packaging value chain is increasingly complex (Dominic, 2013). It consists of many players, in particular raw material producers, packaging converters, the consumer goods industry, retailers, consumers and disposal companies. Assuming that each actor shares some commitment to the goal of sustainability, they cannot simply look at the impact of their own actions to achieve the greatest sustainability gains, but must see in what way they can support other players along the value chain (European Organization for Packaging and the Environment (EUROPEN), 2011).

TABLE 1 shows that the different tools and methods have to meet different standards regarding accuracy and usability depending on the user's requirements. The choice of an environmental assessment tool and the indicators to be evaluated depends on what is going to be compared, where in the packaging design process the assessments are being applied, how the results are being used and where in the supply chain they are being applied (The Consumer Goods Forum, 2011).

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The aim of this review is a comparison of existing methods to assess the environmental impact of packaging. In particular, this review is intended to support environmental and packaging professionals in their search for an appropriate assessment tool.

2. *Comparison of Environmental Assessment Methods and Tools*

To date various methods and tools have been developed and introduced to measure the environmental impact of packaging. These possibilities exhibit specific advantages but, in some cases, also disadvantages. The present section, therefore, aims to present key methods and tools, which can be classified into conventional LCA, simplified (or streamlined) LCA (SLCA) and scorecards.

2.1. *Life Cycle Assessment (LCA)*

The most advanced and simultaneously precise method of assessing the environmental impacts of a given system is a fully executed LCA according to the internationally accepted standards, ISO 14040 and ISO 14044. Recapitulated, LCA compromises the compilation and evaluation of material and energetic inputs and outputs in additional to (potential) environmental impacts of a certain product (e.g. packaging) or process, and considers not only certain conditions, but the entire life cycle. This cycle covers the stages raw material extraction and acquisition, energy and material production, manufacturing, use, end of life treatment and final disposal. Moreover, when conducting an LCA, it is further of the utmost importance to allow full traceability by giving information on the intention for carrying out the study, system boundaries, assumptions, data quality, data sources and allocation procedures. In the case of a fully executed LCA, a mandatory critical review further ensures reliability and scientific validity of the results (ISO, 2006). A considerable amount of literature has been published on LCA (Chen, Yang, Yang, Jiang & Zhou, 2014; Estrela, 2015; McManus & Taylor, 2015). In-depth information on how to set up an LCA

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can be found elsewhere and is not part of this review. Standard textbooks, for example, are provided by Klöpffer and Grahl (2014) and Guinée, de Bruijn, van Duin and Huijbregts (2004). There are also several software solutions currently available on the market, which facilitate the execution of a full LCA. The most commonly known and used are GaBi, SimaPro, Umberto and openLCA (Lüdemann and Feig, 2014). It is important to note, that these software solutions allow the use of several impact assessment methods and the integration of different Life Cycle Inventory databases, which can cause divergent results to some extent (European Commission, 2010, thinkstep, 2017; ecoinvent, 2017). In particular, in the field of packaging, a considerable number of LCAs have been conducted with, in some cases, far-reaching consequences. A specific example is the comparative LCA in the field of beverage packaging, commissioned by the German Federal Ministry for the Environment, which was the basis for the German deposit system on disposable packaging (single-use deposit) (Schonert et al., 2002). Despite the meaningful results of a fully executed LCA, the broad application of LCA is frequently hampered by several factors. These are primarily the extensive data acquisition and preparation as well as the herewith associated cost intensive undertaking of such an analysis. Additionally, expert knowledge is mandatory, which in combination with the aforementioned factors causes particularly small and medium enterprises to outsource such activities to consultants and technical offices (The Consumer Goods Forum, 2011).

2.2. Simplified (or Streamlined) LCA (SLCA)

Against the above mentioned background, a growing demand for easy to use SLCA tools, which can be used without extensive training, is perceptible worldwide. This is, for instance, underlined by the United Nations Environment Programme (UNEP) report “An Analysis of Life Cycle Assessment in Packaging for Food & Beverage Applications”, which points out that a detailed LCA may not be required for every type of decision to be made about packaging design,

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manufacturing or governmental policy making. This emphasizes the importance of a qualitative consideration of the broader life cycle in decision making and SLCA tools for directional analyses (Flanigan et al., 2013). Over recent decades, innumerable SLCA tools have entered the market to accompany these developments. Rousseaux et al. (2017), for example, reviewed and categorized 629 eco-design tools and developed an "Eco-tool-seeker".

Regarding packaging, there are several available tailor-made SLCA tools available, for example PackageSmart, COMPASS, Bilan Environnemental des Emballages (BEE) or Packaging Impact Quick Evaluation Tool (PIQET). These tools allow the analysis of all life cycle stages of a product. However, the possibilities to customize and create new Life Cycle Inventory datasets are limited. Another drawback, when compared to full LCA tools such as GaBi, is that highly complex product systems cannot be modeled or assessed and that the number of impact assessment methods and indicators is limited. Thus, the inevitable trade-off between accuracy and user-friendliness has to be kept in mind when considering the use of an SLCA tool. For example, SLCA tools offer the possibility to easily gain LCA information easily and on the basis of this support decision making. The benefit of such tools is, therefore, always closely related to the accuracy needs and the particular decisions to be supported (Verghese et al., 2010).

Throughout the stage of product design, SLCA information about the impacts of various materials, processes and life cycle phases can be used in refining the product design. This approach is also known as *"eco-design"* (Hetherington, Borrion, Griffiths & McManus, 2014; Rodrigues, Pigosso & McAloone, 2017). At this stage, the application of a full LCA is not appropriate, since the final product details are not yet known and the costs involved would be prohibitive.

SLCA tools typically use pre-defined LCA-steps prompting only for inputs which are easily obtainable (The Consumer Goods Forum, 2011). Simplification occurs at the level of Life Cycle

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Inventory and/or Life Cycle Impact Assessment leading to reduction of the complexity of the modeling process, the data collection efforts and the set of impact categories while facilitating the communication of the results (Arzoumanidis, Salomone, Petti, Mondello & Raggi, 2017).

The SLCA tools reviewed in the present publication are consistently web-based tools with a high degree of user-friendliness. Generally only a basic understanding of life cycle thinking is needed to obtain meaningful results. A good understanding of the assessed product system, however, remains a prerequisite. In most cases, the user interface allows the creation and management of projects, for which certain properties can be specified and they often allow for a general comparative assessment of different scenarios or assumptions. Within a brief period, usually less than a day, a non-LCA-specialist can learn to model packaging systems, compare scenarios and make an environmental impact assessment. Video tutorials as well as free trial versions are available.

The following subsections focus on certain of the SLCA tools used in the context of packaging. A compilation thereof is depicted in Table 2 and the applied method for comparison was testing trial versions.

2.2.1. Packaging Impact Quick Evaluation Tool (PIQET)

The goal of PIQET is to determine the potential environmental impacts associated with the packaging system of a packaged consumer good. Users can create a project, name it and model a packaging system inside this project. The functional unit selected for analysis in PIQET is one kilogram of product on a pallet (packed, including the packaging end-of-life) delivered to a retailer. The modeling of the packaging system consists of assigning certain materials, manufacturing processes, transport and end-of-life scenarios to the different levels of the packaging system. Interestingly, PIQET uses a classification of packaging levels which differs from the standard

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nomenclature. In PIQET there are five packaging levels. Sub-retail and retail unit correlate with the conventionally known primary packaging, merchandising unit with secondary packaging, and traded unit with tertiary packaging. PIQET allows one to conduct a simplified cradle-to-grave LCA. It is possible to vary the recycled content of the packaging material and to analyze different end-of-life scenarios. There is only one impact assessment method implemented in PIQET (with 19 different indicators for categories such as global warming, ozone depletion, land use etc.). The different life cycle stages, which can be assessed in PIQET include material, conversion, filling, wholesale, retail, consumer and end-of-life. Reports and charts with the impact assessment results can be easily generated. In PIQET, simplification takes place at the level of Life Cycle Inventory and Life Cycle Impact Assessment (Life Cycle Strategies Pty Ltd, 2017). An overview of PIQETs functionalities is given by Verghese et al. (2010).

2.2.2. PackageSmart

PackageSmart was developed to allow packaging engineers to rapidly assess new and existing package designs. It is owned by the company EarthShift Global LLC and the structure differs slightly from PIQET. After creating a project, a "package" is defined. The package is the whole system, including primary, secondary and tertiary packaging. The package consists of assemblies, the assemblies themselves consist of subassemblies, and the subassemblies are composed of inventories. An assembly could be, for example, a PET bottle with cap and label. A subassembly could be the PET bottle, which consist of inventories such as polyethylene terephthalate, moulding etc. The assemblies can be assigned to the different packaging levels (primary, secondary, tertiary). A functional unit has to be defined, which is called "Consumer Meaningful Unit of Measure". PackageSmart allows one to conduct a simplified cradle-to-grave LCA. It is possible to vary the recycled content of the packaging material and to analyze different end-of-life scenarios. The user

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can choose between various impact assessment methods. Alongside with different LCA indicators, the cube efficiency (percent of volume in a transport unit occupied by the product) of the packaging can be calculated. Reports and charts depicting the impact assessment results can be easily generated. In PackageSmart, simplification occurs only at the level of life cycle inventory, but not at the level of life cycle impact assessment, due to the fact that the user has to choose between different impact assessments methods (EarthShift Global LLC, 2017).

2.2.3. Comparative Packaging Assessment (COMPASS)

COMPASS stands for COMparative Packaging ASSessment. It was developed by the Sustainable Packaging Coalition and is owned by the company TRAYAK LCC. The structure is similar to PIQET and PackageSmart, although the terminology differs. In the project, one can specify primary, secondary and tertiary packages. The three levels of packages can be combined into one packaging system. Each package consists of components. The components consist of inventories. A component could be, for instance, a plastic bag, and inventories would be in this case the plastic material used (e.g. low-density polyethylene) and the conversion process (e.g. film extrusion). COMPASS does not only allow for the assessment of life cycle metrics (for example: green house gas (GHG) emissions, aquatic toxicity etc.), but also the calculation of so called "non-life-cycle based attributes", including recycled content, sourcing (percentage of certified raw materials) and solid waste. It is also possible to assess health issues. The program checks the packaging for materials of concern. There are three different categories for these materials: C (carcinogen), R (reproductive toxicant) and PBT (persistent, bioaccumulative and toxic). Three lists of substances of concern are integrated into COMPASS (Annex 1 to 6 of the EU REACH regulation, the Toxic Substances Control Act Concern List published by the US EPA and the list of the Californian

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Authorities). In COMPASS, simplification takes place at the level of Life Cycle Inventory and Life Cycle Impact Assessment (Trayak LLC, 2017).

2.2.4. Bilan Environnemental des Emballages (BEE)

BEE is a free-to-use online SLCA tool, which allows the modeling of packaging systems. Materials and processes can be assigned to primary, secondary and tertiary packaging. Distribution, which is called *"Downstream Transportation"*, can also be specified. BEE allows the calculation of six environmental impact indicators, namely global warming potential, abiotic resources depletion, air acidification, water consumption, fresh water as well as marine eutrophication. The datasets account mainly for the French industry, but it is also possibly to select, for example, electricity grid mixes for some other countries as well. Simplification takes place at the level of Life Cycle Inventory and Life Cycle Impact Assessment. The online tool is available in French and in English (Eco-Emballages, 2017).

2.2.5. Instant LCA Packaging™

Instant LCA Packaging™ is a web-based SLCA tool, which allows the user to compare eco-design scenarios for packaging. It was developed for non-expert users. The software is owned by the Intertek Group plc (Intertec Group plc, 2017). RDC Environment, an environmental consultancy, which was acquired by Intertec, offers services such as customization or database development for Instant LCA Packaging™ users (Business Wire, Inc, 2011). This software is not reviewed here, since no trial version is available.

2.2.6. IK-Eco-Calculator

This SLCA tool for the assessment of plastic packaging was developed by the German Industry Association for Plastic Packaging (IK Industrievereinigung Kunststoffverpackungen e.V.). The tool can be used by members of the association and is only applicable for the German industry

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(Möller, Köhler & Moritz, 2016). This software is not reviewed here, since no trial version is available.

2.2.7. EasyLCA

EasyLCA is a software developed by Henkel to make product packaging more sustainable. The tool allows comparison between different packaging types. Their environmental impact can be analyzed during all life cycle stages (Henkel AG & Co KGaA, 2014). This software is not reviewed here, since no trial version is available.EcodEX®

The software EcodEX® is owned by the company Selerant. It is a user-friendly, web-based SLCA tool, which is not packaging-specific. Although, it allows the environmental impact assessment of all different types of consumer goods. The packaging can be easily modeled on the three levels primary, secondary and tertiary packaging. EcodEX® makes it possible to assess the product together with the packaging. It can be connected with existing Enterprise Resource Planning sytems. Five environmental indicators can be calculated, namely global warming potential, land use, water, ecosystem quality - impact 2002+ and non-renewable energy. It is based on the ecoinvent database (Selerant S.r.l., 2017).

2.3. Non-LCA software tools

There are several software tools on the market, which facilitate the evaluation of the environmental performance of packaging, although they do not follow the life cycle approach.

2.3.1. Superpac

Superpac is a packaging optimization software, which is owned by PCS Packaging Software Ltd. It can be extended with a CO_2 software module that can be used to calculate the carbon emissions generated by different packaging solutions (PCS Packaging Software Ltd., 2017). It is, technically

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speaking, not an SLCA tool, since only one indicator (carbon emissions) is assessed and it is not possible to model the full life cycle.

__2.3.2.__ RecyClass

Plastic Recyclers Europe, a Brussels-based association of European plastic recyclers, developed this web-based tool, which evaluates the technical recyclability of the packaging given the current best available technology. The user will gradually approach a rating result by answering questions related to the package. A scale resembling the energy efficiency rating from "A" to "F" is used. A package easy to recycle will receive an "A" rating, while an "F" will indicate that incineration is the only feasible option. The RecyClass tool is only suitable for packaging which is made of plastic, is free from dangerous substances and does not consist of bio- or oxo-degradable plastics. This free-to-use online tool is easy to use and does not require expert knowledge (Plastic Recyclers Europe, 2017).

__2.4. Scorecard__

Next to LCA and SLCA, Scorecards offer the possibility to assess the achievement of certain ecological goals, such as improved recyclability or the reduction of greenhouse gas emissions. In doing so, scorecards can serve as a tool for implementing a sustainability strategy (Hansen & Schaltegger, 2017).

To measure certain achievements, one has to define indicators and metrics. An indicator represents an issue or characteristic an organization wants to measure. A metric is the method used to express an indicator. Metrics are often computational or quantitative, but can also be a qualitative assessment of an indicator. An example for an indicator would be "*greenhouse gas emissions*" and the corresponding quantitative metric would be *"x kg CO_2 equivalents per kg packaging"*. An example for an indicator with a qualitative metric would be *"chain of custody",* expressed with

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the answer *"unknown"* or *"known"* or *"source-certified"* (O'Dea, 2009). These indicators can be derived from an LCA but others, such as *"cube efficiency"* or *"recycled content"*, are easier to retrieve. The complexity of a scorecard depends on the choice of the indicators. The Consumer Goods Forum developed a guideline "Global Protocol on Packaging Sustainability 2.0" (subsequently abbreviated as GPPS) which gives an overview of relevant indicators and the corresponding metrics (The Consumer Goods Forum, 2011).Table 3 shows the GPPS indicators, which are relevant from an environmental point of view.

A scorecard for measuring the sustainability of packaging can be composed of the indicators listed in Table 3. Since the quality and significance of a scorecard is determined by meaningful and appropriate indicators, attention should be paid when it comes to selection thereof (The Consumer Goods Forum, 2011). Choosing too few or inappropriate indicators, for example, carries the risk of simplification and of overlooking of relevant environmental issues, while choosing too many indicators, holds the risk of excessive effort to complete the scorecard, which, ultimately, could decrease the acceptance of the scorecard. In general, scorecards are used for controlling company-internal goals and achievements, and also for communication and control of suppliers. A common example would be a retailer or a major company, which is interested in the way their suppliers address sustainability of their products (Wal-Mart Stores, Inc., 2006). The following subsections present a few examples for scorecards. These case studies have been chosen due to their typical setup and their scope.

2.4.1. Case Study: Woolworths

Woolworths Australia developed a scorecard to measure and control the reduction of the environmental impacts of packaging. Woolworths Australia is a signatory of the Australian Packaging Covenant and made the commitment to review all in-scope products (brand owned by

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Woolworths) against Sustainable Packaging Guidelines (SPG). The SPG must be applied to all new and refurbished private label packaging. In the case of the Woolworths scorecard, most of the indicators concern material composition of the packaging. In most cases the metrics are simple YES or NO answers. Other important indicators are *"recycled content of packaging"*, *"responsible sourcing"* and *"recyclability of packaging"*. Suppliers of in-scope products (private labels, exclusive and controlled brands) have to prove their compliance to the SPG (Woolworths, 2011). Further information as well as the Woolworths scorecard and packaging sustainability guidelines can be retrieved from the Woolworths vendor website (Woolworths, 2017).

2.4.2. Case Study: Wal-Mart

In 2006, Wal-Mart released a packaging scorecard, which asks suppliers to provide information about greenhouse gas emissions, material value, product/packaging ratio, cube utilization, transportation, recycled content, recovery value, renewable energy and innovation. Suppliers have to register via the Wal-Mart Sustainability Hub and provide details. As of 2017 the packaging scorecard is embedded in the broader Sustainability Index (Wal-Mart, Inc., 2016). The "Sustainable Packaging Playbook" is a guidebook for suppliers to improve packaging sustainability. It focuses on three priorities, namely optimized design, source sustainability and recycling. Wal-Mart asks suppliers to improve their Sustainability Index score and provides an overview of sustainable packaging best practices (Wal-Mart, Inc., 2016).

2.4.3. Case Study: World Wide Fund for Nature (WWF)

The WWF developed a paper scorecard. This scorecard can be used by companies to ensure that their paper suppliers meet certain sustainability criteria. Overall the WWF paper scorecard consists of ten questions, structured in three sections. These sections are recycled fibre, virgin fibre as well as greenhouse gases, water pollution and waste. The supplier can choose between different various

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options and so gain points. The score from the single questions can be added to an overall result (WWF, 2007). Certain parts of the WWF paper scorecard are used by Nestlé (Nestlé, 2013).

3. Discussion

The present review aimed to compare the different methods available to assess the environmental impacts of packaging. The appropriate use of one of these methods depends on the company's environmental strategy and the defined goals. If a producer intents to attain a detailed understanding of a product, it is necessary to conduct a full, externally reviewed LCA. Also, if a company wishes to use the environmental data for external communication or for comparative assessment of different products, there is no way to bypass LCA. It is costly to conduct an LCA and requires expert knowledge. This limits the use of LCAs as an environmental assessment method.

SLCAs allow for a quick assessment of different packaging. The SLCA tools reviewed are particularly user-friendly. They are particularly valuable during the design process, due to the fact that different scenarios can easily be compared from an environmental point of view. It is important, however, to know the limitations of these SLCA tools since they only allow the modeling of standard packaging solutions. If, for example, new and innovative polymers are used as raw materials, they might not be representable in the SLCA tool. The underlying Life Cycle Inventory datasets cannot be modified, and detailed modeling of complex life cycles is not feasible. The user has to be aware of the risk of simplification and of the trade-off between accuracy and usability. The use of an SLCA tool does not replace a full LCA. Arzoumanidis et al (2017) reported that the assessment of the same product system, modeled with different SLCA tools, can lead to contrasting results, because of different databases, modeling assumptions and impact assessment methods. This finding implies that SLCA tools should be used only for internal scenario

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comparison. It is problematic to compare the environmental performance of different products calculated with different tools without a good understanding of the used methodology.

Scorecards are management tools to measure the achievement of defined goals. Typically, sustainability scorecards are forms, which have to be completed by contractors or suppliers of large companies. Time and effort depend largely on the selected indicators. If life cycle-indicators are part of the scorecard, then a quantitative assessment has to be made before completing the scorecard. Often, scorecards consist mainly of questions which are relatively easy to answer. Many companies use sustainability scorecards as an environmental management tool. The use of scorecards makes sense, if there is an environmental strategy with quantifiable and measurable goals behind it.

A serious weakness of the scorecard approach is that often the results of the different indicators are aggregated into one single environmental indicator, or, in the case of Wal-Mart, into an overall sustainability score. From a scientific point of view it is problematic because the aggregated result cannot be validated (Carroll, 2007). The weighting of the different indicators always implies a certain degree of subjectivity and is based on more or less robust assumptions (Ahlroth, 2014). The European Organisation for Packaging and the Environment (EUROPEN) criticized the Wal-Mart approach because of flaws in the data and logic. EUROPEN led a lobby in Brussels against a European Parliament proposal for a “Packaging Environmental Indicator” (Carroll, 2007).

The increasing number of tools makes the choice of the most appropriate tool more difficult for companies, resulting in a growing demand for classification of the tools and guidance (Rousseaux et al., 2017). Additionally, the rapid growth in “similar-but-different” tools raised concerns among member states of the European Union, since the proliferation of methods and approaches makes it unnecessarily complicated and expensive to make environmental claims regarding the

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environmental performance of products. Therefore, the member states mandated the development of a European method for the calculation of the environmental footprint of products to the European Commission (Galatola & Pant, 2014). This approach is called Product Environmental Footprint or PEF. The PEF is a multi-criteria measure of the environmental performance of a good or a service throughout its life cycle. Product Environmental Footprint Category Rules (PEFCRs) include specific rules, guidelines and requirements that aim to develop "type III environmental declarations" for any product category. "Type III environmental declarations" are quantitative, LCA-based claims of the environmental aspect of a certain good or service (European Commission & Joint Research Center, 2012). To date, working groups with stakeholders from industry, academia and administrative bodies are developing PEFCRs. PEFCR will not only define the calculation methods, but also prescribe the use of certain background datasets. PEFCR drafts for many different product categories have been submitted to the European Commission, but to date they have not yet been approved (European Commission, 2017). Additionally, there is a PEF Packaging Working Group, which was set up to provide guidance on packaging related modeling and data issues in the ongoing PEF pilot phase (European Commission, 2016). Elaborated PEFCRs would open up the possibility of developing PEF compliant software tools for different product categories, including packaging. Perhaps, the Product Environmental Footprint (PEF) initiative will bring more harmonization into the confusing LCA landscape, although Finkbeiner (2014) raised serious concerns about this issue. According to Finkbeiner, there is a risk that the PEF will end up such as many other "footprint" initiatives and even increase the confusion and proliferation. It has to be stated, that some of the critical issues have been addressed during the pilot phase.

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The results of this review show that the choice of the "right" tool largely depends on the questions asked, on the position in the packaging value chain and on the available resources of the organization (The Consumer Goods Forum, 2011).

Another important finding is that the selection of appropriate indicators is of utmost importance, regardless of the method (LCA, SLCA or Scorecard) used. If, for example, a packaging scorecard focusses on recycling indicators alone, there is a risk of ignoring important environmental issues. For some materials such as aluminum, recycled content is a clear winner over virgin content from an environmental perspective since both scrap collection and reprocessing require far less energy than virgin content production. For others, the outcome is not as clear-cut, either due to the use of renewable energy in virgin material production, inefficient material recovery systems, or due to other reasons (Hermes, 2014). An exclusive focus on carbon emissions implies the risk of shifting the environmental burden from global warming to other environmental impact categories (Finkbeiner, 2009). This finding is supported by a number of studies, which have found that the production of biofuels results in shifting the environmental burden of greenhouse gas emissions to land use change and eutrophication (Taheripour & Tyner, 2012; González-García & García-Rey, 2013).

The choice of indicators should be guided by the general principles of sustainable packaging. Several studies and guidelines have been published on this topic (e.g. Verghese et al., 2012; Jedlicka, 2009; Australian Packaging Covenant, 2010). The indicators themselves also need further development. In the case of packaging, the environmental impact category of marine littering has become a very serious concern, but there is no quantitative indicator to characterize the contribution of a packaging to marine littering.

4. Conclusion & Recommendations

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This review has given an account of and the reasons for the widespread use of packaging-specific environmental assessment tools in industry. The use of these tools is likely to increase during the coming years. In the EU, a certain harmonization can be expected due to the development of the PEF.

Several limitations to this review need to be acknowledged. Not all of the available packaging-specific SLCA tools could be tested, since trial versions were not available in some cases. The scorecards were reviewed only on the basis of a few examples, since the majority of packaging scorecards are used internally and are, therefore, not publicly available.

In a future investigation, the results of the above-mentioned tools for the life cycle of a given packaging system should be directly compared. Further research should be undertaken on new, polymer-based, packaging materials which hold an increasing share of the market, since there is a lack of complete and up-to-date datasets for environmental assessment tools. Further studies should focus on the selection of the most meaningful environmental indicators for packaging solutions and on the refinement of these indicators. Last but not least, the impact of the PEF initiative shall be closely observed and particularly the results of the PEF Packaging Working Group will have the highest relevance for both packaging and sustainability professionals in Europe.

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Conflict of interest

The authors declare to have no conflict of interest.

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TABLE 1 Overview of the three principal methods to assess environmental impacts of packaging, adapted from GPPS (The Consumer Goods Forum, 2011).

Method for the assessment of packaging	Application field	Advantages	Drawbacks
Full LCA (LCA)	A detailed assessment of a product, which can be used for marketing purposes.	Robustness, flexibility Can support marketing claims after external peer review	More costly and long, requires expert knowledge
Streamlined LCA (SLCA)	SLCA can be used as a supportive tool during the design phase.	Quick, low cost,consistent, can be used by non-experts	Low flexibility No capacity to capture specificities Limited possibility to support environmental claims
Scorecards	Management tool to control the suppliers compliance to certain sustainability criteria	Allows retailers and big companies to easily compare their suppliers	Risk of over-simplification Important sustainability aspects might be overlooked, if inappropriate indicators have been chosen

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TABLE 2 Overview of reviewed packaging-specific SLCA tools

Software solution	**Underlying databases**	**Impact assessment methods**	**Life cycle stages**	**References**
Packaging Impact Quick Evaluation Tool - PIQET	Ecoinvent Australia LCA Database BUWAL 250 ETH-ESU 96 IDEAMAT IVAM Database	Australian impact assessment method developed by RMIT University Melbourne	- Material - Conversion - Filling - Wholesale - Retail - Consumer - End-of-Life	Life Cycle Strategies Pty Ltd, 2017 Verghese, Horne, Carre, 2010
PackageSmart Life Cycle Assessment Software	Ecoinvent US LCA database	CML EDIP 2003 EPD (2013) IPCC TRACI	- Materials - Conversion - Distribution - End-of-Life	EarthShift Global LLC, 2017
COMPASS - Comparative Packaging Assessment	Ecoinvent US LCI	Life cycle metrics developed by the Sustainable Packaging Coalition (SPC)	- Manufacture - Conversion - Distribution - End-of-Life	Trayak LLC, 2017
BEE - Bilan Environnemental des Emballages	Ecoinvent PlasticsEurope SYPAL	Six indicators, preselected and partly developed by Eco-Emballages	- Material production - Manufacturing - Transportation - End-of-Life	Eco-Emballages, 2017

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TABLE 3 Packaging sustainability indicators and the corresponding metrics as proposed by GPPS (The Consumer Goods Forum, 2011).

Indicator	**Metric**
NON-LCA Environmental Attributes	
Packaging Weight and Optimization	Weight per packaging constituent, component or system and demonstration of optimization as described by EN 13428 or ISO/CD 18602.
Packaging-to-Product Weight Ratio	Weight of all packaging components used in the packaging system per functional unit.
Material Waste	Mass per packaging constituent, packaging component, or packaging system.
Recycled Content	Recycled material share of total quantity of material used per packaging constituent, packaging component or packaging system.
Renewable Content	a) The percent by weight an the material level according to the amendment to ISO 14021. b) The percent by weight on carbon level according to ASTM D6866.
Chain of Custody	Unknown, known or sourced-certified.
Assessment and Minimization of Substances Hazardous to the Environment	Meeting the requirements of EN 13428 or ISO 18602 on heavy metals and dangerous/hazardous substances.
Production Sites Located in Areas with Conditions of Water Stress or Scarcity	Number or percent of facilities located in an area identified as a stressed or scare water resource area.
Packaging Reuse Rate	a) Reusable – Yes or No according to EN 13429 or ISO/CD 18603. b) Average Reuses
Packaging Recovery Rate	a) Recoverable – Yes, meeting criteria or No. b) Recovery rate [% wt.] with respect to total weight of packaging placed on the market per recovery option.
Cube Utilization	Percent of volume in a transport unit occupied by the product (%).
Life Cycle Indicators - Inventory	
Cumulative Energy Demand (CED)	CED = Cumulative Energy Demand Renewable + Cumulative Energy Demand Nonrenewable [MJ/FU].
Freshwater Consumption	Volume of fresh water consumed per functional unit [m3/FU].
Land Use	[m2 × years / FU] calculated as the sum of all elementary flows of the type land occupation at the inventory level.
Life Cycle Indicators - Impact	
Global Warming Potential (GWP)	Mass of CO_2 equivalents [kg CO2 eq/FU].

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Ozone Depletion	Mass of CFC-11 equivalents [kg CFC-11 eq/FU].
Toxicity, Cancerous	Potential relative to a reference substance, e.g. [kg C_2H_3Cl eq/FU or kg C_6H_6 air eq/FU].
Toxicity, Non-Cancerous	Potential relative to a reference, e.g. toluene, expressed as mass equivalents, e.g. [kg toluene eq/FU].
Particulate Respiratory Effects	Mass of PM10 equivalents [kg PM10 eq/FU].
Ionizing Radiation	Mass of kg U235 equivalents [kg U235 eq/FU].
Photochemical Ozone Creation Potential (POCP)	Mass of non-methane volatile organic compound equivalents [kg NMVOC eq/FU].
Acidification Potential	Mass of SO_2 equivalents [kg SO2 eq/FU].
Aquatic Eutrophication	Phosphorous equivalents in freshwater [kg P eq/FU]. Nitrogen equivalents in saltwater [kg N eq/FU].
Freshwater Ecotoxicity Potential	Ecotoxicity potential relative to a unit of mass of a reference substance, e.g. 1,4-Dichlorobenzene [kg 1,4 DB eq/FU].
Non-Renewable Resource Depletion	Relative to a reference substance e.g. a) kg antimony equivalents/FU or b) Person reserve [kg/FU].