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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

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 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.

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 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].

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.

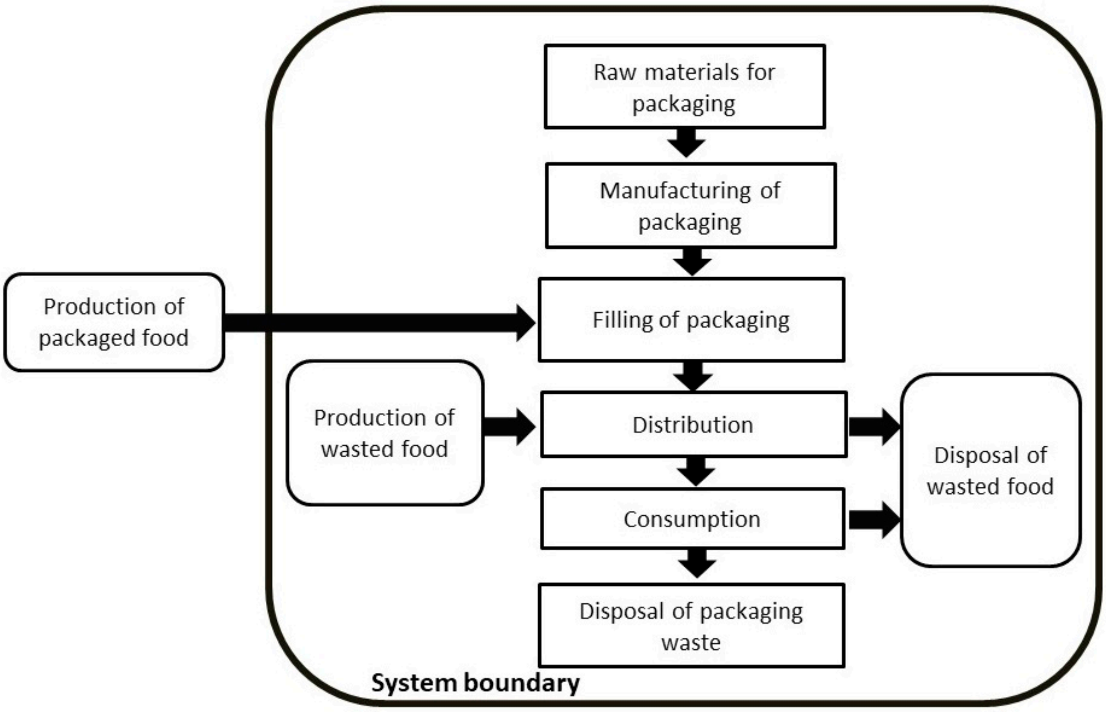

Figure 1. Inclusion of packaging-related food losses and waste (FLW) into packaging LCA (adopted from Grant et al., 2015).

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].

2.4. Measuring the Circularity of Packaging

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.

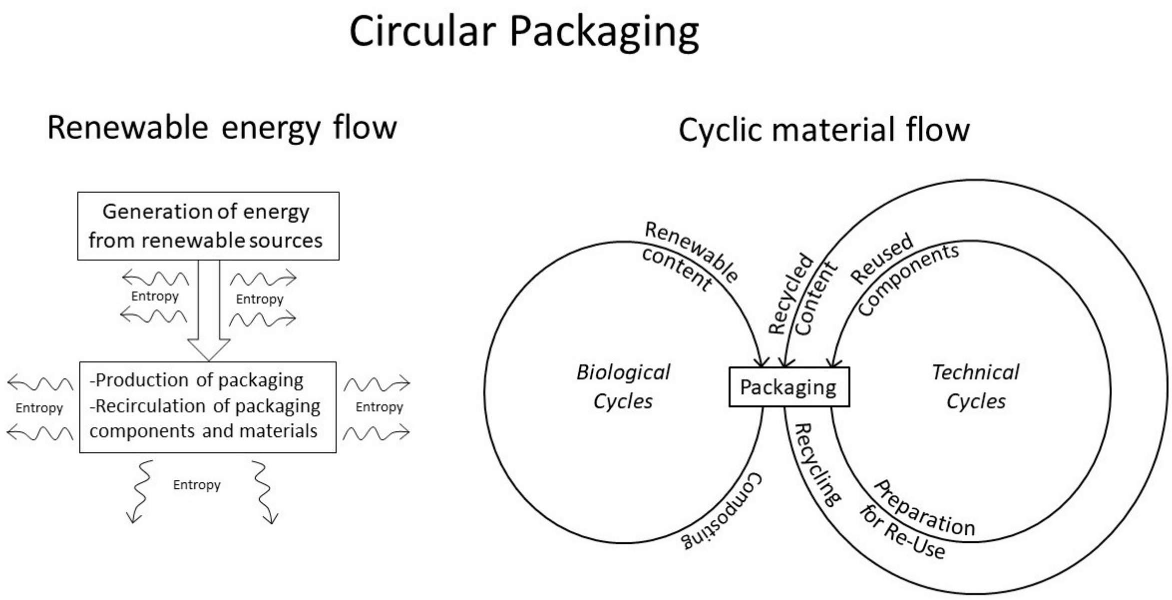

Figure 2. Circular packaging concept based on Korhonen et al. [14] and Braungart & McDonough [15].

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 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.

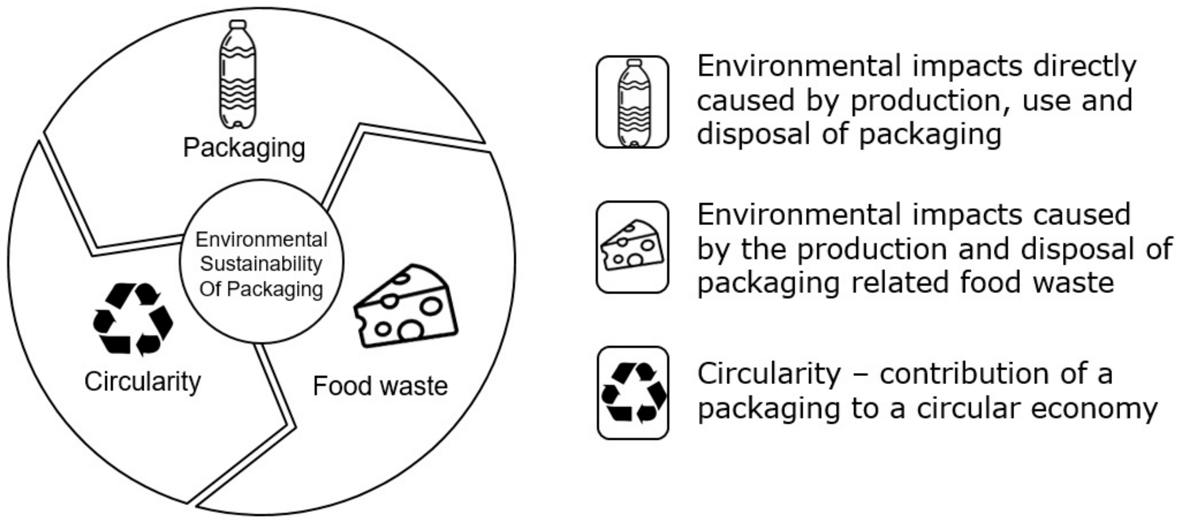

Figure 3. The three aspects of the environmental sustainability of food packaging.

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.
- 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.

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].

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 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 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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References

1. Singh, P.; Wani, A.A.; Langowski, H.-C. Introduction: Food Packaging Materials. In *Food Packaging Materials: Testing & Quality Assurance*; Singh, P., Wani, A.A., Langowski, H.-C., Eds.; Taylor & Francis Group: London, UK, 2017; pp. 1–9.
2. Verghese, K.; Lewis, H.; Lockrey, S.; Williams, H. *The Role of Packaging in Minimising Food Waste in the Supply Chain*; CHEP Australia: Melbourne, Australia, 2013.
3. Verghese, K.; Lewis, H.; Lockrey, S.; Williams, H. Packaging's Role in Minimizing Food Loss and Waste Across the Supply Chain. *Packag. Technol. Sci.* **2015**, *28*, 603–620. [CrossRef]

4. Flanagan, L.; Frischknecht, R.; Montalba, T. *An Analysis of Life Cycle Assessment in Packaging for Food & Beverage Applications*; UNEP/SETAC Life Cycle Initiative: Nairobi, Kenia, 2013.
5. Pongrácz, E. The environmental impacts of packaging. In *Environmentally Conscious Materials and Chemicals Processing*; Kutz, M., Ed.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2007; pp. 237–278.
6. Gustavsson, J. *Global Food Losses and Food Waste: Extent, Causes and Prevention*; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 2011.
7. Wohner, B.; Pauer, E.; Heinrich, V.; Tacker, M. Packaging-Related Food Losses and Waste: An Overview of Drivers and Issues. *Sustainability* **2019**, *11*, 264. [CrossRef]
8. Molina-Besch, K.; Wikström, F.; Williams, H. The environmental impact of packaging in food supply chains—Does life cycle assessment of food provide the full picture? *Int. J. Life Cycle Assess.* **2018**, *21*, 492. [CrossRef]
9. Pilz, H. *Vermeidung von Lebensmittelabfällen durch Verpackung*; denkstatt GmbH: Vienna, Austria, 2017.
10. Grant, T.; Barichello, V.; Fitzpatrick, L. Accounting the Impacts of Waste Product in Package Design. *Procedia CIRP* **2015**, *29*, 568–572. [CrossRef]
11. Büsser, S.; Jungbluth, N. The role of flexible packaging in the life cycle of coffee and butter. *Int. J. Life Cycle Assess.* **2009**, *14*, 80–91. [CrossRef]
12. Cyclos-HTP. *Verification and Examination of Recyclability: Revision 3.6*; HTTP: Aachen, Germany, 2018.
13. Hopewell, J.; Dvorak, R.; Kosior, E. Plastics recycling: Challenges and opportunities. *Philos. Trans. R. Soc. B* **2009**, *364*, 2115–2126. [CrossRef] [PubMed]
14. Korhonen, J.; Honkasalo, A.; Seppälä, J. Circular Economy: The Concept and its Limitations. *Ecol. Econ.* **2018**, *143*, 37–46. [CrossRef]
15. Braungart, M.; McDonough, W. *Cradle to Cradle–Remaking the Way We Make Things*; North Point Press: New York, NY, USA, 2002.
16. European Commission. *Closing the Loop—An EU Action Plan for the Circular Economy*; European Commission: Brussels, Belgium, 2015.
17. European Parliament and Council. *Directive 94/62/EC on Packaging and Packaging Waste*; European Parliament and Council: Brussels, Belgium, 1994.
18. European Commission. *Circular Economy: New Rules Will Make EU the Global Front-Runner in Waste Management and Recycling*; European Commission: Brussels, Belgium, 2018.
19. Ellen MacArthur Foundation. Eleven Companies Take Major Step towards a New Plastics Economy. 2018. Available online: https://www.ellenmacarthurfoundation.org/news/11-companies-take-major-step-towards-a-new-plastics-economy (accessed on 18 December 2018).
20. European Parliament and Council. *Directive 2008/98/EC on Waste and Repealing Certain Directives*; European Parliament and Council: Brussels, Belgium, 2008.
21. Schmidt, J.H.; Holm, P.; Merrild, A.; Christensen, P. Life cycle assessment of the waste hierarchy-a Danish case study on waste paper. *Waste Manag.* **2007**, *27*, 1519–1530. [CrossRef]
22. Ashby, M.F. *Materials and the Environment: Eco-Informed Material Choice*; Butterworth-Heinemann: Oxford, UK, 2013.
23. Arena, U.; Mastellone, M.L.; Perugini, F.; Clift, R. Environmental Assessment of Paper Waste Management Options by Means of LCA Methodology. *Ind. Eng. Chem. Res.* **2004**, *43*, 5702–5714. [CrossRef]
24. Wellenreuther, F. *Potential Packaging Waste Prevention by the Usage of Flexible Packaging and Its Consequences for the Environment: Executive Summary Commissioned by Flexible Packaging Europe (FPE)*; FPE: Heidelberg, Germany, 2014.
25. Franklin Associates. *LCI Summary for 8 Coffee Packaging Systems*; American Chemistry Council: Prairie Village, USA, 2008.
26. Steiner, R.; Jungbluth, N.; Büsser, S. *LCA of Packed Food Products the Function of Flexible Packaging—Case Study*; Butter: Uster, Switzerland, 2008.
27. Garavand, F.; Rouhi, M.; Razavi, S.H.; Cacciotti, I.; Mohammadi, R. Improving the integrity of natural biopolymer films used in food packaging by crosslinking approach: A review. *Int. J. Biol. Macromol.* **2017**, *104*, 687–707. [CrossRef]
28. Joint Research Center. The FOR-LEARN Online Foresight Guide. 2008. Available online: http://forlearn.jrc.ec.europa.eu/guide/4_methodology/framework.htm (accessed on 7 January 2019).
29. Verghese, K.; Lewis, H.; Fitzpatrick, L. *Packaging for Sustainability*; Springer: London, UK, 2012.

30. The Consumer Goods Forum. *Global Protocol on Packaging Sustainability 2.0*; The Consumer Goods Forum: Issy-les-Moulineaux, France, 2011.
31. Sustainable Packaging Coalition. *Definition of Sustainable Packaging*; Sustainable Packaging Coalition: Charlottesville, VA, USA, 2011.
32. Walmart. *Sustainable Packaging Playbook: A Guidebook for Suppliers to Improve Packaging Sustainability*; Walmart: Bentonville, AR, USA, 2016.
33. NEPC. *National Environment Protection (Used Packaging Materials) Measure 2011*; NEPC: Sydney, Australia, 2011.
34. Australian Packaging Covenant. *Sustainable Packaging Guidelines*; Australian Packaging Covenant: Sydney, Australia, 2011.
35. *CEN/TC 261. Packaging—Requirements for Packaging Recoverable by Material Recycling: EN 13430:2004*; European Committee for Standardization: Brussels, Belgium, 2004.
36. *CEN/TC 261. Packaging. Requirements for Packaging Recoverable through Composting and Biodegradation. Test Scheme and Evaluation Criteria for the Final Acceptance: EN 13432:2000*; European Committee for Standardization: Brussels, Belgium, 2000.
37. *CEN/TC 261. Packaging—Requirements Specific to Manufacturing and Composition—Prevention by Source Reduction: EN 13428:2004*; European Committee for Standardization: Brussels, Belgium, 2004.
38. *CEN/TC 261. Packaging—Requirements for Packaging Recoverable in the Form of Energy Recovery, Including Specification of Minimum Inferior Calorific Value: EN 13431:2004*; European Committee for Standardization: Brussels, Belgium, 2004.
39. *CEN/TC 261. Packaging–Reuse: EN 13429:2004*; European Committee for Standardization: Brussels, Belgium, 2004.
40. ISO. *Life Cycle Assessment–Principles and Framework: 14040:2006*; International Organization for Standardization: Geneva, Switzerland, 2006.
41. ISO. *Environmental Management—Life Cycle Assessment—Requirements and Guidelines*; International Organization for Standardization: Geneva, Switzerland, 2006.
42. Hunt, R.G.; Franklin William, E. LCA–How it came about. *Int. J. Life Cycle Assess.* **1996**, *1*, 4–7. [CrossRef]
43. Schonert, M.; Motz, G.; Meckel, H.; Detzel, A.; Giegrich, J.; Ostermayer, A.; Schorb, A.; Schmitz, S. *Ökobilanz für Getränkeverpackungen II*; Umweltbundesamt: Berlin, Germany, 2002.
44. Von Falkenstein, E.; Wellenreuther, F.; Detzel, A. LCA studies comparing beverage cartons and alternative packaging: Can overall conclusions be drawn? *Int. J. Life Cycle Assess.* **2010**, *15*, 938–945. [CrossRef]
45. Humbert, S.; Rossi, V.; Margni, M.; Jolliet, O.; Loerincik, Y. Life cycle assessment of two baby food packaging alternatives: Glass jars vs. *plastic pots. Int. J. Life Cycle Assess.* **2009**, *14*, 95–106. [CrossRef]
46. Dinkel, F.; Kägi, T. *Ökobilanz Getränkeverpackungen*; Bundesamt für Umwelt Schweiz: Bern, Switzerland, 2014.
47. Brander, M.; Tipper, R.; Hutchison, C.; Davis, G. *Consequential and Attributional Approaches to LCA*; Springer: Edinburgh, UK, 2010.
48. Ekvall, T.; Azapagic, A.; Finnveden, G.; Rydberg, T.; Weidema, B.P.; Zamagni, A. Attributional and consequential LCA in the ILCD handbook. *Int. J. Life Cycle Assess.* **2016**, *21*, 293–296. [CrossRef]
49. Allacker, K.; Mathieux, F.; Manfredi, S.; Pelletier, N.; de Camillis, C.; Ardente, F.; Pant, R. Allocation solutions for secondary material production and end of life recovery: Proposals for product policy initiatives. *Resour. Conserv. Recycl.* **2014**, *88*, 1–12. [CrossRef]
50. Allacker, K.; Mathieux, F.; Pennington, D.; Pant, R. The search for an appropriate end-of-life formula for the purpose of the European Commission Environmental Footprint initiative. *Int. J. Life Cycle Assess.* **2017**, *22*, 1441–1458. [CrossRef]
51. Kägi, T. Implementation of Recycling Systems: The Delusive Role of LCA. In Proceedings of the 25th SETAC Europe Annual Meeting, Barcelona, Spain, 3–7 May 2015.
52. Koffler, C.; Finkbeiner, M. Are we still keeping it "real"?: Proposing a revised paradigm for recycling credits in attributional life cycle assessment. *Int. J. Life Cycle Assess.* **2018**, *23*, 181–190. [CrossRef]
53. Schrijvers, D.L.; Loubet, P.; Sonnemann, G. Critical review of guidelines against a systematic framework with regard to consistency on allocation procedures for recycling in LCA. *Int. J. Life Cycle Assess.* **2016**, *21*, 994–1008. [CrossRef]

54. Nicholson, A.L.; Olivetti, E.A.; Gregory, J.R.; Field, F.R.; Kirchain, R.E. End-of-life LCA allocation methods: Open loop recycling impacts on robustness of material selection decisions. In Proceedings of the 2009 IEEE International Symposium on Sustainable Systems and Technology (ISSST), Phoenix, AZ, USA, 18–20 May 2009; pp. 1–6.
55. Miller, S.; Theis, T. Comparison of Life-Cycle Inventory Databases: A Case Study Using Soybean Production. *J. Ind. Ecol.* **2008**, *10*, 133–147. [CrossRef]
56. Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-Ruiz, E.; Weidema, B. The ecoinvent database version 3 (part I): Overview and methodology. *Int. J. Life Cycle Assess.* **2016**, *21*, 1218–1230. [CrossRef]
57. Sonnemann, G.; Vigon, B. *Global Guidance Principles for Life Cycle Assessment Databases: Shonan Guidance Principles*; United Nations Environment Programme: Nairobi, Kenia, 2011.
58. Baitz, M. *GaBi Database & Modelling Principles 2013*; Version 1.0; PE International: Stuttgart, Germany, 2013.
59. Joint Research Centre (JRC); Institute for Environment and Sustainability (IES). *ILCD Handbook–Background Document: Analysis of Existing Environmental Impact Assessment Methodologies for Use in Life Cycle Assessment*; JRC: Ispra, Italy, 2010.
60. Li, T.; Zhang, H.; Liu, Z.; Ke, Q.; Alting, L. A system boundary identification method for life cycle assessment. *Int. J. Life Cycle Assess.* **2014**, *19*, 646–660. [CrossRef]
61. Ekvall, T.; Weidema, B.P. System boundaries and input data in consequential life cycle inventory analysis. *Int. J. Life Cycle Assess.* **2004**, *9*, 161–171. [CrossRef]
62. Van Hoof, G.; Vieira, M.; Gausman, M.; Weisbrod, A. Indicator selection in life cycle assessment to enable decision making: Issues and solutions. *Int. J. Life Cycle Assess.* **2013**, *18*, 1568–1580. [CrossRef]
63. Steinmann, Z.J.N.; Schipper, A.M.; Hauck, M.; Huijbregts, M.A.J. How Many Environmental Impact Indicators Are Needed in the Evaluation of Product Life Cycles? *Environ. Sci. Technol.* **2016**, *50*, 3913–3919. [CrossRef] [PubMed]
64. Klöpffer, W.; Grahl, B. *Life Cycle Assessment: A Guide to Best Practice*; Wiley-VCH: Weinheim, Germany, 2014.
65. Hunsager, E.A.; Bach, M.; Breuer, L. An institutional analysis of EPD programs and a global PCR registry. *Int. J. Life Cycle Assess.* **2014**, *19*, 786–795. [CrossRef]
66. Palminger, A. *Closable Flexible Plastic Packaging*; Product Category Classification: Un CPC 36490; CPC: Stockholm, Sweden, 2017.
67. Milà i Canals, L.; Vigon, B.; Wang, F. *Global Guidance for Life Cycle Impact Assessment Indicators*; UNEP/SETAC Life Cycle Initiative: Nairobi, Kenia, 2016; Volume 1.
68. European Commission. *Commission Recommendation of 9 April 2013 on the Use of Common Methods to Measure and Communicate the Life Cycle Environmental Performance of Products and Organisations*; European Commission: Brussels, Belgium, 2013.
69. Bruijn, P. *Proposal for a New PEF EoL Formulas*; European Commission: Brussels, Belgium, 2016.
70. Weidema, B. Harnessing the End-of-Life Formula. 2015. Available online: https://lca-net.com/blog/harnessing-the-end-of-life-formula/ (accessed on 17 May 2018).
71. Wolf, M.-A.; Chomkhamsri, K. *Integrated Approach and Formula for Recycling, Reuse and Energy Energy in LCA and Environmental Footprinting*; maki Consulting: Berlin, Germany, 2014.
72. Finkbeiner, M. Product environmental footprint—Breakthrough or breakdown for policy implementation of life cycle assessment? *Int. J. Life Cycle Assess.* **2014**, *19*, 266–271. [CrossRef]
73. Sala, S.; Castellani, V.; Zampori, L. *Supporting Information to the Charcterisation Factors of Recommended EF Impact Assessment Method: New Models and Differences with ILCD*; EU: Ispra, Italy, 2018.
74. Lehmann, A.; Bach, V.; Finkbeiner, M. Product environmental footprint in policy and market decisions: Applicability and impact assessment. *Integr. Environ. Assess.* **2015**, *11*, 417–424. [CrossRef] [PubMed]
75. European Commission. *PEFCR Guidance Document: Guidance for the Development of Product Environmental Footprint Category Rules (PEFCRs), Version 6.3*; European Commission: Ispra, Italy, 2018.
76. PEF Packaging Working Group. *Packaging Working Group Guidance Document*; PEF Packaging Working Group: Brussels, Belgium, 2016.
77. Wikström, F.; Verghese, K.; Auras, R.; Olsson, A.; Williams, H.; Wever, R.; Grönman, K.; Kvalvåg Pettersen, M.; Møller, H.; Soukka, R. Packaging Strategies that Save Food: A Research Agenda for 2030. *J. Ind. Ecol.* **2018**, *14*, 1346. [CrossRef]
78. Heller, M.C.; Selke, S.E.M.; Keoleian, G.A. Mapping the Influence of Food Waste in Food Packaging Environmental Performance Assessments. *J. Ind. Ecol.* **2018**, *5*, 134. [CrossRef]

79. Buzby, J.; Wells, H.F.; Axtman, B.; Mickey, J. *Supermarket Loss Estimates for Fresh Fruit, Vegetables, Meat, Poultry and Seafood and Their Use in the ERS Loss-Adjusted Food Availability Data*; United States Department of Agriculture, Economic Research Service: Washington, DC, USA, 2009.
80. Lebersorger, S.; Schneider, F. *Aufkommen an Lebensmittelverderb im Österreichischen Lebensmittelhandel: Endbericht im Auftragder ECR-Arbeitsgruppe Abfallwirtschaft 2014*; Universität für Bodenkultur: Vienna, Austria, 2014.
81. Vernier, A. *Pertes et Gaspillages Alimentaires: L'état des Lieux et Leur Gestion par Étapes de la Chaîne Alimentaire*; Ministere de l'Environnement, de l'Energie et de la Mer: Paris, France, 2016.
82. Vahedikia, N.; Garavand, F.; Tajeddin, B.; Cacciotti, I.; Jafari, S.M.; Omidi, T.; Zahedi, Z. Biodegradable zein film composites reinforced with chitosan nanoparticles and cinnamon essential oil: Physical, mechanical, structural and antimicrobial attributes. *Colloid Surf. B* **2019**, *177*, 25–32. [CrossRef] [PubMed]
83. Cacciotti, I.; Mori, S.; Cherubini, V.; Nanni, F. Eco-sustainable systems based on poly(lactic acid), diatomite and coffee grounds extract for food packaging. *Int. J. Biol. Macromol.* **2018**, *112*, 567–575. [CrossRef] [PubMed]
84. ISO. *Environmental Labels and Declarations—Self-Declared Environmental Claims (Type II Environmental Labelling): ISO 14021:2016*; International Organization for Standardization: Geneva, Switzerland, 2016.
85. UNFCCC. ANNEX 28–Definition of renewable biomass. In *CDM Executive Board Report (EB23)*; United Nations Framework Convention on Climate Change: Bonn, Germany, 2006.
86. Ellen MacArthur Foundation. *GRANTA Design. Circularity Indicators: An Approach to Measuring Circularity*; Ellen MacArthur Foundation: London, UK, 2015.
87. Frischknecht, R.; Wyss, F.; Büsser Knöpfel, S.; Lützkendorf, T.; Balouktsi, M. Cumulative energy demand in LCA: The energy harvested approach. *Int. J. Life Cycle Assess.* **2015**, *20*, 957–969. [CrossRef]
88. European Commission. *Development of a Weighting Approach for the Environmental Footprint*; European Commission: Ispra, Italy, 2018.
89. Stocker, T.; Boschung, J.; Qin, D.; Bex, V.; Midgley, P.; Tignor, M.; Plattner, G.-K.; Allen, S.; Xia, Y.; Nauels, A. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2013.
90. CITEO. TREE–Test de la REcyclabilité des Emballages. 2018. Available online: http://tree.citeo.com/ (accessed on 7 January 2019).
91. Packaging, S.A. *Design for Recycling for Packaging and Paper in South Africa*; National Recycling Forum: Bryanston, South Africa, 2017.
92. Pack4Recycling. Recyclability of Your Packaging. Do the Test! Available online: https://www.pack4recycling.be/en/content/industrial-packaging (accessed on 7 January 2019).
93. RECOUP. Plastic Packaging—Recyclability by Design. 2017. Available online: http://www.recoup.org/downloads/info-required?id=478&referrer=http%3A%2F%2Fwww.recoup.org%2Fp%2F275%2Fpublications (accessed on 7 January 2019).
94. Plastic Recyclers Europe. RecyClass, The Recyclability Tool for Plastic Package. 2018. Available online: http://www.recyclass.eu/en/home/ (accessed on 1 June 2018).
95. Gironi, F.; Piemonte, V. Bioplastics and Petroleum-based Plastics: Strengths and Weaknesses. *Energ. Source Part A* **2011**, *33*, 1949–1959. [CrossRef]
96. Ceci-Renaud, N.; Tarayoun, T. *Comportements D'achat en Présence D'affichage Environnemental: Les Enseignements d'une Enquête par Expériences de Choix*; Ministère de L'environnement: Paris, France, 2016.
97. Galatola, M.; Pant, R. Reply to the editorial "Product environmental footprint—breakthrough or breakdown for policy implementation of life cycle assessment?" written by Prof. Finkbeiner (Int J Life Cycle Assess 19(2):266–271). *Int. J. Life Cycle Assess.* **2014**, *19*, 1356–1360. [CrossRef]
98. Bach, V.; Lehmann, A.; Görmer, M.; Finkbeiner, M. Product Environmental Footprint (PEF) Pilot Phase—Comparability over Flexibility? *Sustainability* **2018**, *10*, 2898. [CrossRef]
99. Lehmann, A.; Bach, V.; Finkbeiner, M. EU Product Environmental Footprint—Mid-Term Review of the Pilot Phase. *Sustainability* **2016**, *8*, 92. [CrossRef]
100. Steffen, W.; Richardson, K.; Rockström, J.; Cornell, S.E.; Fetzer, I.; Bennett, E.M.; Biggs, R.; Carpenter, S.R.; de Vries, W.; de Wit, C.A.; et al. Sustainability. Planetary boundaries: Guiding human development on a changing planet. *Science* **2015**, *347*, 1259855. [CrossRef]

101. De Wit, M.; Hoogzaad, J.; Ramkumar, S.; Friedl, H.; Douma, A. *The Circularity Gap Report: An Analysis of the Circular State of the Global Economy*; Circle Economy: Amsterdam, The Netherlands, 2018.
102. Cacciotti, I.; Nanni, F. Poly(lactic) acid fibers loaded with mesoporous silica for potential applications in the active food packaging. In *AIP Confererence Proceedings*; American Institute of Physics: College Park, MD, USA, 2016; p. 270018.
103. Dugmore, T.I.J.; Clark, J.H.; Bustamante, J.; Houghton, J.A.; Matharu, A.S. Valorisation of Biowastes for the Production of Green Materials Using Chemical Methods. *Top. Curr. Chem.* **2017**, *375*, 46. [CrossRef]
104. European Commission. *A Sustainable Bioeconomy for Europe: Strengthening the Connection between Economy, Society and the Environment: Updated Bioeconomy Strategy*; Publications Office of the European Union: Luxembourg, 2018.
105. Kale, G.; Kijchavengkul, T.; Auras, R.; Rubino, M.; Selke, S.E.; Singh, S.P. Compostability of bioplastic packaging materials: An overview. *Macromol. Biosci.* **2007**, *7*, 255–277. [CrossRef]
106. Rossi, V.; Cleeve-Edwards, N.; Lundquist, L.; Schenker, U.; Dubois, C.; Humbert, S.; Jolliet, O. Life cycle assessment of end-of-life options for two biodegradable packaging materials: Sound application of the European waste hierarchy. *J. Clean. Prod.* **2015**, *86*, 132–145. [CrossRef]
107. Deutsche Umwelthilfe. *Bioplastik in der Kompostierung: Ergebnisbericht–Umfrage*; Deutsche Umwelthilfe: Radolfzell, Germany, 2018.