Multi-dimensional sustainability assessment of product-packaging combinations

MuDiSa: A calculation tool to assess the sustainability of product-packaging combinations in multiple dimensions of sustainability

Marieke Brouwer, Ulphard Thoden van Velzen

PUBLIC

WAGENINGEN
UNIVERSITY & RESEARCH

Multi-dimensional sustainability assessment of product-packaging combinations

MuDiSa: A calculation tool to assess the sustainability of product-packaging combinations in multiple dimensions of sustainability

Authors: Marieke Brouwer, Ulphard Thoden van Velzen

Institute: Wageningen Food & Biobased Research

This study was carried out by Wageningen Food & Biobased Research, subsidised and commissioned by the TKI Agri Food and funded by STV, KIDV, CBL, FNLI, GFH and NRK.

Wageningen Food & Biobased Research
Wageningen, July 2023

Public

Report 2442
DOI: 10.18174/633072

WFBR Project number: 6234192300
BAPS number: BO-64-001-022
Version: Final
Reviewer: I.W. Smeding
Approved by: N. Koenderink
Carried out by: Wageningen Food & Biobased Research
Subsidised and commissioned by: the Dutch Ministry of Agriculture, Nature and Food Quality, TKI Agri Food
Funded by: STV, KIDV, CBL, FNLI, GFH, NRK
This report is: Public

The client is entitled to disclose this report in full and make it available to third parties for review. Without prior written consent from Wageningen Food & Biobased Research, it is not permitted to:

a. partially publish this report created by Wageningen Food & Biobased Research or partially disclose it in any other way;
b. use this report for the purposes of making claims, conducting legal procedures, for (negative) publicity, and for recruitment in a more general sense;
c. use the name of Wageningen Food & Biobased Research in a different sense than as the author of this report.

The research that is documented in this report was conducted in an objective way by researchers who act impartial with respect to the client(s) and sponsor(s).

PO box 17, 6700 AA Wageningen, The Netherlands, T + 31 (0)317 48 00 84, E info.wfbr@wur.nl, www.wur.eu/wfbr.

Contents

Summary

This report is part of a public-private partnership project “Wrap or waste” (BO-64-001-022). In this project the goal is to quantify the relationship between alternative preservation techniques and packaging materials on the one hand, and quality of perishable food products on the other hand, thereby helping the industry make optimal, well-founded and sustainable choices. Packaging and especially plastic packaging is increasingly under scrutiny from politicians, NGO’s and various other stakeholders, for its role in climate change and planetary pollution. This calls for a re-evaluation of the currently applied packaging formats. A change in packaging methods, however, has major ramifications on product quality, the product supply chain organisation and the packaging materials themselves. Via case studies on specific product-packaging combinations, quantitative data is collected and tools are developed that help to provide concrete answers that companies can use for their packaging choices. This public report describes MuDiSa, a calculation tool for multi-dimensional sustainability assessment, that is developed in this project. The results of the case studies are described in separate public summaries.

The developed sustainability assessment tool calculates multiple sustainability indicators in an attempt to include the most important aspects of packaging sustainability: the effect of food loss & waste, the circularity of the packaging, the (circular) recycling of the packaging and the effect the packaging has on plastic soup formation due to littering. This tool is therefore unique in its kind, as to our knowledge no other product-packaging sustainability assessment tool includes all these aspects of packaging sustainability.

The calculation tool works with case specific data about the packaging and food product and background data including the emission factors of materials and processes and recycling efficiencies. All this data is combined into multiple sustainability indicators that describe the sustainability of the product-packaging combinations in different dimensions of sustainability. The sustainability indicators are:

- Greenhouse gas emissions, GWP-100 [kg CO_2 equivalents / kg of consumed food]
- Packaging to product weight ratio, PPR [%]
- Recycled content indicator, ReConI [%]
- Recyclability indicator, RI [%]
- Circular recyclability indicator, CRI [%]
- Recycling Chain Indicator, RCI [%]
- Renewable content indicator, RenewI [%]
- Organic recyclability indicator, ORI [%]
- Littering prevention indicator, LPI [%]
- Material Circularity Indicator, MCI [%]

1 Introduction

This report is part of a public-private partnership project “Wrap or waste” (BO-64-001-022). In this project the goal is to quantify the relationship between packaging and alternative preservation techniques & materials on the one hand, and the quality of perishable food products on the other hand, thereby helping the industry make optimal, well-founded and sustainable choices. Changing packaging methods affects product quality, the product supply chain and the packaging materials themselves. Via case studies on specific product-packaging combinations, quantitative data are collected and tools are developed that help to provide concrete answers that companies can use for their packaging choices.

In 2020 this project started with a consortium of Dutch organisations that are described in Figure 1. They are active in the fields of food waste, developing knowledge on sustainable packaging and/or they represent companies active in the food and packaging sector. Wageningen Food & Biobased Research (WFBR) is the research partner and overall project coordinator. Private companies are joining with specific products that are used as case studies. All partners contribute both financially and in kind. The project is co-funded by the Dutch Ministry of Agriculture, Nature and Food Quality via Topsector Agri & Food. WFBR performed this study independently and objectively.

Consortium Wrap or Waste:

- Samen tegen Voedselverspilling (STV)
- Kennisinstituut Duurzaam Verpakken (KIDV)
- Federatie Nederlandse Levensmiddelen Industrie FNLI
- NRK Verpakkingen
- Centraal Bureau Levensmiddelenhandel (CBL)
- GroentenFruit Huis (GFH)
- Wageningen Food & Biobased Research (WFBR)

Figure 1 Consortium partners Wrap or Waste.

This public report describes the calculation tool (MuDiSa) that has been developed in this project. This sustainability assessment tool calculates the emissions of greenhouse gasses associated with packaged food products along their life cycle and other indicators of sustainability. The tool has a generic set-up that allows the calculation of the greenhouse gas emissions and sustainability indicators of packages (both single-use and reusable) made from various materials containing a specific (food) product. The tool is built in Excel. Within this project the tool has been used to assess the sustainability of different cases within this project. The results of each of the case studies (Figure 2) are described in confidential reports that were shared with the case owners. Public summaries of these case studies are published.

Cases Wrap or Waste:

- Coffee packaging (We Wonder Company)
- Strawberry packaging (Greenery/Bio4pack)
- Bakery ingredients bags (Dawn Foods)
- Cheese packaging (Vergeer)
- Lettuce packaging (Growx)

Figure 2 Cases Wrap or Waste

This report is organized as follows:

- Chapter 2 describes the goal and scope of the calculation tool,
- Chapter 3 describes the input data (LCI) that is needed as input in the calculation tool,
- Chapter 4 describes the background data,
- Chapter 5 describes the tool outputs (indicators), the calculation methodology and how these are expressed,
- In Chapter 6 some final remarks are made on the development of the calculation tool.

2 Goal and scope

Sustainability assessment is a complex matter. As an example, to analyse the sustainability of a food packaging, not only the packaging itself needs to be considered, but also the effect on the shelf life of the food product and the related food losses. When assessing the sustainability of a food product-packaging combination, various aspects of sustainability need to be taken into account:

- the effect of food loss & waste,
- the circularity of the packaging,
- the (circular) recycling of the packaging,
- and the effect the packaging has on plastic soup formation due to littering.

As this is not possible with existing tools, within the project, a new dedicated tool has been developed.

Multiple life cycle assessment (LCA) tools for the environmental impact assessment of packages have been developed over the years. Commercially available tools are for instance PIQET (Verghese et al., 2010) and COMPASS (Verghese et al., 2012; Compass, 2011). These tools are expensive, can only be used within their limitations and can provide conflicting advises (Speck et al., 2015). These tools are not suitable to guide packaging design processes, but can only be used to evaluate the impact of complete packaging designs. Another more recently developed tool is EnvPack (Ligthart et al. 2019) which allows packaging designers to assess the environmental impact of packages that they are developing with several impact assessment methods. Additionally, the Dutch Knowledge Institute for Sustainable Packaging (KIDV) provides a Sustainable Packaging Compass (KIDV, 2022) on their website which can be used for free by packaging designers to assess the sustainability of different packaging types in three aspects: recyclability, circularity and environmental impact.

These LCA-based tools fail to include the effect of food loss & waste and therefore neglect this major contributor to the environmental impacts of packaged food products. Furthermore, these tools are merely LCA based (with the exception of the Sustainable Packaging Compass that includes recyclability and circularity) and therefore neglect important dimensions of sustainability that are currently not expressed within LCA-based tools, such as: recyclability, circularity and estimated contribution to the formation of plastic pollution.

Life cycle assessment (LCA) methodologies attempt to provide a complete overview of the environmental impacts related to products and processes by defining several environmental impact categories and combine them in a midpoint or endpoint as a single environmental score. However, not all of the important aspects of packaging sustainability are included in a traditional LCA. For instance, LCA methodology does not include a widely supported way to include the impacts of plastic soup formation due to littering of packaging types, although new approaches have been suggested (Woods, 2021). Also, LCA is not a suitable method to assess the circularity and/or recyclability of a packaging design. However, the greenhouse gas emissions that are a consequence of the packaging design in a product-packaging combination are important as an indicator of packaging sustainability for two reasons: it does provide insight in the contribution to climate change and it provides the opportunity to include the effects of food losses to the assessment. Furthermore, the GWP-100 (or cumulative energy demand) is a good predictor for the environmental impact of fossil-based packaging materials (Huijbrechts, 2006). WFBR proposes an assessment tool that includes the most important aspects of packaging sustainability: the greenhouse gas emissions (including the effect of food losses) in combination with several additional sustainability indicators to assess the sustainability of the product-packaging combinations in multiple dimensions.

The calculated emission of greenhouse gasses is split in four contributions:

1) emissions due to the production of the food product,
2) emissions due to the production of the packaging,
3) emissions due to the treatment of the packaging waste and
4) the avoided emissions due to the use of recycled materials or energy recovered from the materials.

In general the calculations in this tool follow the attributional allocations rules (the actual environmental impacts of the processes related to the product and packaging). The only exception is the inclusion of the avoided emissions which might be interpreted as a consequential approach (the calculations include the consequential effects of the decision made in the product life cycle). As these avoided emissions are important in the comparison of packaging types, especially when packaging types could be recycled, these avoided emissions are included in the results as a separate contribution. The system boundaries of the greenhouse gas calculations are the production of the food item and the package on the one side and the waste management of both the food waste and the packaging waste on the other side. This implies that the following aspects of the life cycle are considered in the calculation:

- Impact of the food: production, food losses and food waste management,
- Impact of the package: production of all the components, assembly and waste management,
- Reusability of packages,
- Packaging transport.

The functional unit of these calculations is 1 kg of consumed food. More details about the choice of this functional unit are provided in Chapter 5.

Additionally, several indicators are calculated to assess the overall sustainability of the packaged products. These indicators fill the gap for the environmental impacts that can currently not be calculated with basic LCA methodology, such as recyclability, circularity and the potential contribution to littering. The scope of this tool is by default the Netherlands, but it can be adjusted when required.

The tool is developed to assess and compare the sustainability of different packaging options for a specific (food) product. The indicators in this tool are a basic version to map the packaging sustainability on these multiple dimensions. The indicators should therefore be interpreted to show a range and not an exact number.

Hence, this assessment tool provides the ability to assess the sustainability of product-packaging combinations on a higher level including all important aspects that define packaging sustainability: the effect of food loss & waste, the circularity of the packaging, the (circular) recycling of the packaging and the effect the packaging has on plastic soup formation due to littering.

3 Product-packaging specific input data

As input for the sustainability assessment, input data are required. In this chapter we describe the required data, both about the (food) product and the packaging. Different packaging options can be compared. Information on the life cycle of the packaged product (life cycle inventory, LCI) is collected. This data is different for the different product-packaging combinations and scenarios. In this chapter, these inputs are further described.

3.1 Information about the food product

3.1.1 Type of food product and packaging volume

The type of food product that is packaged and the packaging volume are defined in the LCI. This data needs to be entered in the calculation tool. The type of food product can be selected from a list of food products that is in the background database of the calculation tool (see section 4.1). The amount of food product that a packaging is designed to contain is named the "packaging volume". This parameter is conveniently entered in terms of the food product's weight in grams.

3.1.2 Food losses

For a proper assessment of the impact of a food package not just the amount of consumed food product is relevant, but the total amount of food that had to be produced to fulfil that consumption, hence in including the losses in the supply chain. The functional unit of the calculation of the greenhouse gas emissions related to the product-packaging combination (1 kg of consumed foods) is translated to the total amount of produced foods. See also section 5.1.1 for a more detailed explanation on the incorporation of food losses in the calculations. Therefore, an expected percentage of food losses is needed as input in the calculations.

In the value chain multiple types of food losses occur. Food is lost due to the expiration of the best-before date (FL_{exp}), due to poor handling, due to poor empty-ability of the packages, etc. The tool is focussing on food losses in the supply chain and at the consumer due to expiration of the best before date / use before date, but can be expanded with additional types of food loss when that is meaningful for the analysis. In many cases, however, the percentage of food losses is not known. In those cases, the share of food product that will not be consumed and is expected to be lost, can be predicted with the reciprocal general relationship between food loss and shelf life, see Equation 1. This relationship is used to estimate the effect of shelf-life changes on the food loss rate. In Annex 1 this reciprocal general relationship is explained in more detail.

Symbol	**Meaning**	**Unit**
FL_{exp}	Food loss due to exceedance of expiration date	%
SL	Shelf life	Days

$$FL_{exp} = 0.557 \times SL^{-0.844}$$

Equation 1: Relation between food losses due to exceedance of the expiration date and the shelf life.

3.2 Information about the packaging

3.2.1 Packaging components

The packaging components are defined in the LCI. For each individual component the weight needs to be known. This weight can be determined by simply weighing the separate components. In case of multilayer films the weight of separate layers is determined based on the layer thickness (from the material specification), density of the individual materials and the measured surface area of the packaging . In some cases, for more complex components, the producer specifications can be used to enter the weight per material. Moreover, the material, material class, material origin and the production process can be selected from dedicated lists that are available in the background database of the calculation tool (see section 4.1).

3.2.2 Reusable packaging

For reusable packages the LCI requires input on the amount of reuse loops ($Amount\ of\ loops_{package}$), which is set at 1 for single-use packages. Moreover the amount of energy (kWh), water (L) and detergent (kg) used per reuse loop must be known or estimated and entered in the tool.

3.2.3 Transport

The impact of transporting product-packaging combinations is included in the calculation of the greenhouse gas emissions only when it is relevant. Therefore, information about the transport movements per reuse loop (or for one reuse loop in case of a single use packages) is needed as information. For every transport movement the type of vehicle, type of transport movement (to consumer, for a reuse loop or to the end-of-life process) can be selected from dedicated lists that are available in the background database of the calculation tool (see section 4.2). Moreover, the amount of kilometres (km) that are related to the transport movement, and the amount of packages that fit in the vehicle is needed. The amount of packages that can be transported in a vehicle can be defined based on the packaging volume and type. See also section 5.1.3 for a more detailed explanation on the impact of transport in the calculations.

3.2.4 Packaging waste scenario

The impact of the end-of-life of the packaging is automatically calculated with the input data of the packaging components. More information about these calculations is provided in section 4.1.4. Additionally, the packaging type and collection route can be chosen. The collection route (recovery from mixed municipal solid waste (MSW), separate collection, incineration of MSW or organic waste) is based on the end-of-life scenario. Furthermore, it needs to be defined if the entire packaging is recyclable and/or composable. For every packaging component the type of material (at the end-of-life stage) can be selected. Also for all the separate components it needs to be defined if the packaging component is recyclable and/or compostable.

3.2.5 Binary operators

Next to all data about the product-packaging life cycle (LCI) that is used to calculate the greenhouse gas emissions four additional binary operators are used as input for the sustainability indicators. These four questions are:

- Is the packaging recyclable? [yes/no] (same as mentioned in 3.2.4)
- Is the packaging circularly recyclable? [yes/no] In other words, can the recycled packaging material be used in similar applications as the current packaging.
- Is the packaging used and discarded in home or out of home? [in home/out of home]
- Is the packaging listed in EU Single Use Plastics directive[1] as one of the ten plastic objects most abundantly found on beaches? [yes/no]

---

[1] https://eur-lex.europa.eu/eli/dir/2019/904/oj

4 Background data

The tool calculates the global warming potential after 100 years in terms of carbon dioxide equivalents of the packaged product and the indicators for the other dimensions of sustainability based on information of the life cycle of the packaged product. Background information is used to be able to execute these calculations. This background information is available in databases that are part of the calculation tool. The LCI input data (as described in Chapter 3) defines which data from these databases is used to calculate the results. This chapter describes the background data and their source.

4.1 Greenhouse gas emissions related to separate products and processes

Greenhouse gas emission factors of specific materials and production processes are available in underlying databases, which include common packaging materials and conversion processes. These data are expressed in kg CO_2 equivalents (eq.) per kg, kWh, etc. For the following products and processes greenhouse gas emission factors are included in the databases:

- Food products (kg CO_2 eq. / kg)
- Materials (kg CO_2 eq. / kg)
- Production processes (packaging) (kg CO_2 eq. / kg)
- End-of-life processes (kg CO_2 eq. / kg)
- Reuse processes:
    - Energy (kg CO_2 eq. / kwh)
    - Water usage (kg CO_2 eq. / kg)
    - Detergent (kg CO_2 eq. / kg)

Most data in these databases originate from the Ecoinvent databases (Wernet et al., 2016 & Paasen et al, 2019). These data are market data (so including unit processes to be able to put these materials on the market such as transport, factories, etc.) and are generated with the IPCC 2013 GWP 100a V1.03 method (IPCC, 2013). Data from literature or own estimates are used to fill the database in case the data was unavailable in Ecoinvent (see Annex 2 for a list of details). In case a novel material is used to produce the packaging, a separate calculation can be made to determine the greenhouse gas emissions related to the materials and production process per kg of material. The result of this calculation can be added in the database, so it will be available for future use.

For greenhouse gas emissions related to the end-of-life processes the background database includes emissions related to both the process and avoided emissions due to the usage of recycled materials or energy that is recovered from the incineration process.

The calculation of the greenhouse gas emissions is further explained in Section 5.1.

4.2 Data to calculate greenhouse gas emissions related to transport

Emissions related to the transport of the product-packaging combination are calculated with the well-to-wheel approach (see section 5.1.3). Hence, as background data the emission factor of diesel and the diesel consumption per vehicle are used for the calculations in the sustainability tool (see Annex 2 for the sources of this data).

4.3 Recycling data

For all packaging types the collection efficiency, sorting efficiency and recycling efficiency is included in the underlying database. These efficiencies are used in the calculation of greenhouse gas emissions related to the packaging waste treatment, the material circularity indictor and the recycling chain indicators. These efficiencies are based on previous research of WFBR (Thoden van Velzen et al., 2017, 2019, 2020, 2022; Brouwer et al., 2017, 2019).

5 Outputs and calculations

WFBR proposes MuDiSa: a calculation tool that can assess the sustainability of product-packaging combinations, which includes the most important aspects of packaging sustainability, as explained in Chapter 2. These aspects are: the effect of food loss & waste, the circularity of the packaging, the (circular) recycling of the packaging and the effect the packaging has on plastic soup formation due to littering. The tool will be used to compare packaging types for a specific food product on a general level. Multiple indicators are defined to assess several dimensions of sustainability:

- Greenhouse gas emissions, GWP-100 [kg CO_2 equivalents / kg of consumed food]
- Packaging to product weight ratio, PPR [%]
- Recycled content indicator, ReConI [%]
- Recyclability indicator, RI [%]
- Circular recyclability indicator, CRI [%]
- Recycling Chain Indicator, RCI [%]
- Renewable content indicator, RenewI [%]
- Organic recyclability indicator, ORI [%]
- Littering prevention indicator, LPI [%]
- Material Circularity Indicator, MCI [%]

These indicators will provide a broad overview of the important aspects of packaging sustainability and are developed as a basic version to compare packaging types in multiple dimensions of sustainability. An example of output graphs from MuDiSa is shown in Figure 3. These indicators can be further developed over time, and new indicators can be added to the system in future. The calculation method for these indicators is explained in this chapter.

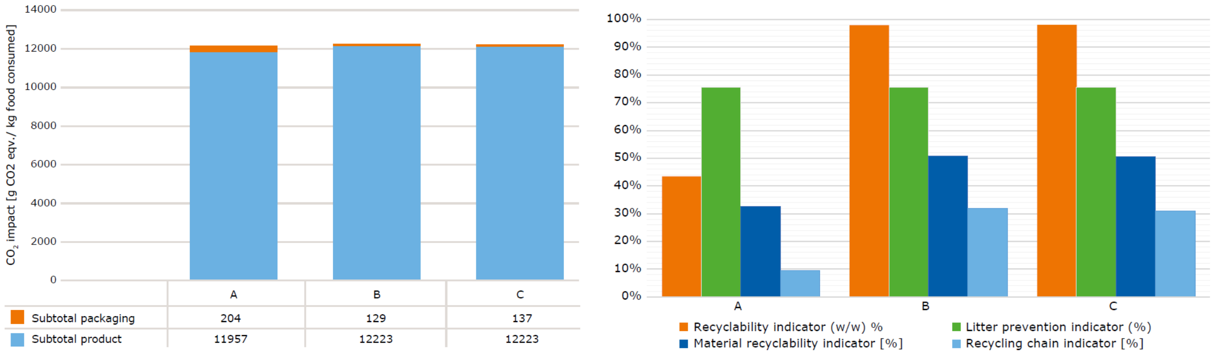

Figure 3 ***Examples of output graphs from MuDiSa. In this case three packaging types (A, B and C) were compared in multiple dimensions of sustainability. The left graph shows the greenhouse gas emissions in grams CO_2 equivalents per kg of consumed food. The right graph shows four other sustainability indicators that were relevant for this specific comparison (RI, LPI, MCI and RCI).***

5.1 Greenhouse gas emissions (GWP-100)

The global warming potential over 100 years (GWP-100) is calculated for packaged food products using a life cycle assessment approach. System boundaries are the production of food and packages at the start and the End-of-Life treatment of both food waste and packaging waste at the end. The functional unit is 1 kg of consumed food and the results are expressed as kg CO_2 equivalents (eqv.) emitted per kg of consumed food. This functional unit enables us to consider packaging related food losses in the calculation of greenhouse gas emissions. At the same time, the tool includes the effects of reusable packaging and transport movements (with the well-to-wheel approach). Furthermore, greenhouse gas emissions are calculated in the conventional way. The approach to calculate greenhouse gas emissions, including food waste, packaging reusability, transport and used product in the packages at the end-of-life stage is explained in more detail in the next paragraphs.

5.1.1 Incorporation of food waste

The impacts of food waste are included in the LCA calculation by the method that was proposed by Wikström et al. in 2014 (Wikström, et al., 2014). In essence this implies that the functional unit is the amount of consumed food ($m_{\text{consumed food}}$). In this tool the functional unit is 1 kg of consumed food. Due to the fact that there are multiple losses in the production chain the amount of produced food ($m_{\text{produced food}}$) is higher to compensate for the sum of all losses in the value chain (FL), see Equation 2. In section 3.1.2. the data collection of food losses (FL) is described.

$$m_{produced\ food} = \frac{m_{consumed\ food}}{(1 - FL)}$$

Equation 2: The relation between the amount of produced food, the amount of consumed food and the total food losses in the value chain.

An important parameter in the analysis is the amount of packaging units that are required to fulfil the functional unit. This amount of packaging units is calculated from the ratio between the amount of produced food and the contents of the package, see Equation 3.

$$Number_{packaging\ units} = \frac{m_{produced\ food}}{packaging\ content}$$

Equation 3: The number of required packaging units is related to the mass of the produced food and the content per packaging unit.

5.1.2 Dealing with reusable packages in the tool

The number of packages required to be produced to fulfil the functional unit can be calculated from the number of packaging units and the average amount of loops a reusable package can be used. So for a single use package the amount of loops is one and the number of produced packages simply equals the number of required packaging units. For reusable packages this amount of produced packages is reduced with increasing loop numbers, according to Equation 4.

$$Number_{packages\ produced} = \frac{Number_{packaging\ units}}{Amount\ of\ loops_{package}}$$

Equation 4: The amount of produced packages that are required to fulfil the functional unit is calculated from the amount of packaging units that are required and the average amount of loops a package can be used.

Reusable packages also need to be collected, washed and inspected, implying that with every loop reusable packages use water, energy and detergents and these impacts also need to be accounted for in the calculation of greenhouse gas emissions. The amount of times packages have to be transported, washed and inspected is named the "amount of recuperations" ($\text{Amount}_{\text{recup.}}$). The amount of recuperations can be calculated as the required number of packages multiplied by the amount of loops minus one (Equation 5).

$$Amount_{recup.} = Number_{packages} \times \left(Amount\ of\ loops_{pack.} - 1\right)$$

Equation 5: The amount of recuperations that are required to fulfil the functional unit.

The amount of recuperations that are required to fulfil the functional unit ($\text{Amount}_{\text{recup.}}$) is used to calculate greenhouse gas emissions related to the reuse processes by multiplying this amount by the used amount of energy, water or detergent per reuse loop (from section 3.2.2) and the emission factor related to these materials (from section 4.1).

5.1.3 Dealing with the transport of packages (well-to-wheel approach)

For packages, transport can be calculated in two ways: the ton*km approach and the well-to-wheel approach. In other studies, such as (Ruiter & Haffmans, 2021), it was already noted that the packaging weight has a disproportionate effect in calculations with the ton*km approach. The ton*km approach multiplies the weight that is transported with the transport distance, which suggests that a doubling in packaging weight equals a doubling in ton*km in the transport scenario. However, for packaging transport it is more likely that the vehicles simply transport a heavier load. Therefore, the well-to-wheel approach is used in calculations of greenhouse gas emissions related to transport. With the well-to-wheel approach the packaging volume is the basis of the calculations and defines how much transport movements and vehicles are needed to fulfil the functional unit. This approach relates, in our opinion, better to the practice of transporting packaging in which the packaging volume plays an important role in filling the vehicles.

The greenhouse gas emissions of the transport movements are calculated per transport movement, which is a combination of a distance, vehicle and transport type: to consumer, for a reuse loop or to the end-of-life process. The amount of packages that is transported to fulfil the functional unit ($Packages_{transport\ movement}$) is different for each type of transport movement. To fulfil the functional unit, all packaging units ($Number_{packaging\ units}$) need to be send to the consumer, regardless if these packaging units come from a reuse process or if these are new packages that originate directly from production. For a reuse loop the amount of recuperations ($\text{Amount}_{\text{recup.}}$) equals the amount of packages that are transported. At the end of life, all the packages that are produced ($Number_{packages\ produced}$) are discarded. Therefore, at the end of life, the amount of packages that are transported equals the amount of packages that are produced ($Number_{packages\ produced}$). Subsequently, the greenhouse gasses related to the packaging movement are calculated with Equation 6.

Symbol	Meaning	Unit
$GWP100_{transport\ movement}$	Greenhouse gas emissions related to transport movement	CO_2 eq.
$Packages_{transport\ movement}$	Amount of packages that is transported	#
$Packages_{vehicle}$	Amount of packages that would fit in one vehicle of the type that is used for the transport movement	#
$Distance$	Transport distance for the movement	km
$Consumption_{vehicle}$	Diesel consumption of the vehicle that is used for the transport movement	L/km
EM_{Diesel}	Emission factor of diesel	kg CO_2 eq. / L

$$GWP100_{transport\ movement} = \frac{Packages_{transport\ movement}}{Packages_{vehicle}} \times Distance \times Consumption_{vehicle} \times EM_{Diesel}$$

Equation 6: The calculation of greenhouse gas emissions related to a transport movement.

The sum of the contribution to the emission of each transport movement yields the total emission of greenhouse gasses that is related to the transport.

5.1.4 Calculating the overall greenhouse gas emissions

The total greenhouse gas emission related to the product-packaging combination is the sum of the contributions of the emissions that are related to food production, packaging production, food waste management, packaging waste management and packaging transport. This is expressed as a weight of greenhouse gas emitted in relation the functional unit: the weight of food consumed. Therefore the results are expressed in the unit of kg CO_2 eqv. / kg consumed food.

- The greenhouse gas emission as a result of the food production is calculated by multiplying reported emission factors (from section 4.1) with the mass of produced food (from section 3.1).
- The greenhouse emission as a result of the packaging materials and production is calculated on the basis of the mass of the required packaging components (from section 3.2). So the number of the produced packages is multiplied with the mass of the packaging component and multiplied with the emission factor of the material of which the component is produced and the production method that

is used to produce the component (from section 4.1). The sum of the contribution to the emission of each component yields the total emission of greenhouse gasses that is related to the production of the packages.

- The greenhouse gas emission as a result of the food waste is calculated over the part of the food that is not consumed but wasted (see section 5.1.1). This amount is multiplied with the emission factor for anaerobic digestion and composting of the food waste (from section 4.1).
- The greenhouse gas emission as a result of the packaging waste management is calculated by using the recycling chain data from section 4.3. This data is used to calculate which component of the packages is recycled or incinerated. For each material present in the packages the concomitant emission factors of either the recycling process and the incineration process are used (from section 4.1). Also the avoided production and energy production (electricity and heat) are separately accounted for with the data from section 4.1).

5.2 Packaging to product ratio (PPR)

The packaging to product ratio (PPR) is calculated as the total weight of the package (from section 3.2.1) divided by the total weight of the product-packaging combination (section 3.2.1 and section 3.1.1) and is expressed in percent. Hence, this indicator shows how much packaging is used in relation to the product volume. This indicator was already introduced in a previous report (Thoden van Velzen, 2020). It should be noted that light-weighting alone will not always provide the most sustainable packaging options, therefore this indicator is only used besides the other sustainability indicators.

5.3 Recycled content indicator (ReConI)

This is a new indicator that describes the share of recycled material that is used to produce the packaging. It is expressed with a percentage. It equals 0% in case no recycled content is present and 100% is case the entire packaging is made of recycled material.

5.4 Recyclability indicator (RI)

The recyclability indicator (RI) expresses whether or not a packaging can be recycled (section 3.2.5) and the mass fraction of the package that ends up in a secondary resource (recycled material) (section 3.2.4 and section 3.2.1). It is expressed in percent. 0% implies that the package is not recycled and 100% means that the package is fully recyclable. This indicator expresses "recyclability" and hence not what is actually happening in the recycling value chain. Therefore it doesn't account for collection, sorting and recycling losses. This indicator was already introduced in a previous report (Thoden van Velzen, 2020).

5.5 Circular recyclability indicator (CRI)

The circular recyclability indicator (CRI) expresses whether or not a packaging can be recycled into a similar application (section 3.2.5) and the mass fraction of the package that ends up in the secondary resource (recycled material) that is produced (section 3.2.4 and section 3.2.1). It is expressed in percent. 0% implies that the package cannot be recycled to the same type of package and 100% would mean that the package is fully recyclable to a new package. This indicator doesn't account for collection, sorting and recycling losses. This indicator was already introduced in a previous report (Thoden van Velzen, 2020).

5.6 Recycling chain indicator (RCI)

The recycling chain indicator (RCI) expresses the recycling chain efficiency for a specific packaging type. This recycling chain efficiency is calculated by multiplying the collection efficiency, sorting efficiency and recycling efficiency of the main material into a targeted secondary resource (section 3.2.4 and section 4.3). A part of the packages will not become the targeted secondary resource, but will be recycled into a mixed secondary resource via a mixed sorted product or a recycling side product. This part of the packages will be added to the RCI for 50%. In case the packaging consists of several packaging components that are collected for recycling separately (for instance lids and caps are sometimes separated during use or the recycling process from the main packaging component and processed separately), for each component the concomitant RCI is calculated (section 3.2.1). The sum of contribution of each component yields the total RCI.

5.7 Renewable Content Indicator (ReNewI)

This is a new indicator that expresses the share of renewable material of which the packaging is made. The unit is percentage and it runs from 0% (no renewable content) to 100% (completely made from renewable materials). A renewable material means: not based on fossil feedstock.

5.8 Organic Recyclability Indicator (ORI)

This new indicator describes the recyclability of the capsule material within the organic waste treatment processes and quantifies the mass fraction of the capsule that is completely transformed in biomethane, CO2 or humus. It is expressed in a percentage, where 100% implies that the packaging is fully recyclable organically, while 0% means the packaging remains unaltered and cannot be recycled organically.

5.9 Litter prevention indicator (LPI)

The litter prevention indicator (LPI) expresses the likelihood that the package will not contribute to road-side and/or marine litter. This indicator is proposed in a previous study (Thoden van Velzen, 2020) and is still in development. This indicator is expressed in percent. 100% means that the package doesn’t form persistent litter and 0% means that the chance that this package will be littered is maximal.

The first version of this indicator was a product of three factors. The first two are binary operators (section 3.2.5). In case the article is commonly used out-of-home (BI_{use}) the first operator is 1, otherwise 0.5. In case the article is a known single-use plastic and commonly found on beaches (BI_{SUP}) then the second operator is 1, otherwise 0.5. The third factor is the mass share of non-degradable materials ($c_{non-degradable}$), which are materials that are expected to degrade within one year in a moderate climate (section 3.2.1). These three factors together are used to calculate the littering prevention indicator, see equation 7.

$$LPI = 100\% - \left(BI_{use} \times BI_{SUP} \times c_{non-degradable}\right)$$

Equation 7: Original calculation of the litter prevention indicator.

This calculation has one major disadvantage. For reuse systems the amount of loops is not considered. Since for every additional loop the chance that the package will be littered will reduce, we added a reciprocal value of the amount of loops ($Amount\ of\ loops_{package}$) to the equation (section 3.2.2). For single use packages, the amount of loops is 1 and nothing changes to the calculation. For reusable packages with many loops even a package that is used out-of-home (at railway stations, at bus stations, in parks, on streets, etc.) and of which the alternative SUP is commonly found on the European beaches will have a high LPI.

$$LPI = 100\% - \left(BI_{use} \times BI_{SUP} \times c_{non-degradable} \times \frac{1}{Amount\ of\ loops_{package'}} \right)$$

Equation 8: Updated calculation of the litter prevention indicator.

This litter prevention indicator is a first version to show the effects of road-side and/or marine littering as a sustainability indicator for packaging types. This indicator enables packaging types to be compared amongst each other in the likelihood that they will contribute to persistent litter. Of course, this indicator can be further developed including for instance the accumulation potential of the specific material that is used for the packaging or the years it will take for a material to safely degrade in the natural environment. This is especially relevant for biodegradable plastics. This accumulation potential is further developed at WFBR, but not yet ready to be implemented in the sustainability assessment tool. For now, the effect of compostable/biodegradable materials has been added to the calculation tool in a simplified manner: materials that are not bio-degradable in the natural environment in less than one year, but are degradable more quickly than non-degradable materials (timeline between 1 and 30 years) are added for 50% as degradable content.

5.10 Material circularity indicator (MCI)

The material circularity indicator that is used in this study is developed by the Ellen Mc Arthur foundation (Ellen MacArthur Foundation, 2019). This indicator is expressed in percent. 100% means that the package is fully circular and 10% means the packaging is fully linear. In comparison to the other indicators that are used in this study, this indicator will thus never result in 0% as 10% is the lowest result. To calculate this indicator, we followed the approach of the Ellen Mc Arthur foundation. This indicator includes the packaging recycling, recycling efficiencies, reuse/lifespan and material origin, which data is collected in the input data of the calculation tool (section 3.2.1, section 3.2.2, section 3.2.4, section 4.3). This indicator includes the use of renewable content that is processed with organic waste as a circular material use. So in case a material is made of 100% renewable and compostable material and is for 100% composted the MCI result will be 100%.

A factor in the calculation of the MCI that is more difficult to determine, is the so-called 'Utility-factor', that describes the life span of the product/packaging. In the current version of the sustainability tool we use the amount of reuse loops ($Amount\ of\ loops_{package}$) as a parameter to describe the 'Utility'. We did not use the 'light-weighting' option, as this discriminator is difficult to justify in this comparative sustainability assessment for two reasons. Firstly, the optimal packaging weight can be different for the different packaging formats and materials that we compare with this tool. Secondly, when food losses can be reduced by using more material the sustainability of a product-packaging combination can be improved and therefore light-weighting is not always the most sustainable option. Hence, in the current version of the tool the Utility factor is set to 1 for single-use packages and to the amount of reuse loops for reusable packages.

6 Final remark

This report described the sustainability assessment tool that is developed and used in the public-private partnership project “Wrap it or waste it”. This tool is developed to be able to compare packaging types for a certain food product in multiple dimensions of sustainability. This tool results in a combination of widely accepted sustainability indicators, such as the calculation of the greenhouse gas emissions, and more novel / experimental sustainability indicators, such as the litter prevention indicator. Both types of indicators are needed to clarify the different dimensions of packaging sustainability. The calculation tool is an evolving tool that is being adjusted according to the latest insights and needs for new use cases. The sustainability tool and the indicators are already successfully used in multiple test cases to explain the differences in sustainability dimensions between various packaging types.

Literature

Broeren, M.L.M, Kuling, L., Worrell, E., Shen. L., 2017. Environmental impact assessment of six starch plastics focusing on wastewater-derived starch and additives. Resources, Conservation and Recycling, Volume 127, 2017, Pages 246-255, ISSN 0921-3449, https://doi.org/10.1016/j.resconrec.2017.09.001.

Brouwer, M. T., Thoden van Velzen, E. U., Augustinus, A., Soethoudt, H., De Meester, S., & Ragaert, K., 2018. Predictive model for the Dutch post-consumer plastic packaging recycling system and implications for the circular economy. *Waste Management*, *71*, 62-85. https://doi.org/10.1016/j.wasman.2017.10.034

Brouwer, M., Picuno, C., Thoden van Velzen, E. U., Kuchta, K., De Meester, S., & Ragaert, K. 2019. The impact of collection portfolio expansion on key performance indicators of the Dutch recycling system for Post-Consumer Plastic Packaging Waste, a comparison between 2014 and 2017. Waste Management, 100, 112-121. https://doi.org/10.1016/j.wasman.2019.09.012

Coffigniez, F., Matar C., Gaucel, S., Gontard, N., Guilbert, S., Guillard, V., 2021. "The Use of Modeling Tools to Better Evaluate the Packaging Benefice on Our Environment" Frontiers in Sustainable Food Systems 5 . DOI: 10.3389/fsufs.2021.634038

COMPASS, SPC (Sustainable Packaging Coalition). COMPASS (Comparative Packaging Assessment). 2011; www.design-compass. org. [Accessed February 2022].

Ellen MacArthur Foundation. 2019. Circularity indicators - an approach to measuring circularity. Cowen: Ellen MacArthur Foundation, https://ellenmacarthurfoundation.org/material-circularity-indicator

European Commission, 2018, Environmental impact assessment of innovative bio-based products, doi:10.2777/251887

Huijbrechts, M.A.J., Rombouts, L.J.A., Hellweg, S., Frischknecht, R., Hendriks, J., Meent, van der, D., Ragas, A.M.D., Reijnders, L., Struijs, J. 2006. Is cumulative energy demand a useful indicator for the environmental performance of products? Environmental science & technology. Vol. 40., No. 3, 2006.

IPCC (Intergovernmental Panel on Climate Change). 2013. IPCC Fifth Assessment Report. The Physical Science Basis. http://www.ipcc.ch/report/ar5/wg1/.

KIDV website, Sustainable Packaging Compass, 2022. https://kidv.nl/the-sustainable-packaging-compass-1 . [Accessed February 2023].

Ligthart, T.N., Thoden van Velzen, E.U., and Brouwer M., 2019. *EnvPack an LCA-based tool for environmental assessment of packaging chains. Part 1: scope, methods and inventory of tool.* The International Journal of Life Cycle Assessment, 2019 **24**(5): p. 900-914.

Ligthart, T.N. and T.M.M. Ansems, 2019. *EnvPack, an LCA-based tool for environmental assessment of packaging chains: Part 2: influence of assessment method on ranking of alternatives.* The International Journal of Life Cycle Assessment, 2019. **24**(5): p. 915-925.

Nguyen, T.T.T., Wilson, B.G. 2010. „Fuel consumption estimation for kerbside municipal solid waste (MSW) collection activities" Waste Management & Research, 2010: 28: 289–297 DOI: 10.1177/0734242X09337656

Paassen, M, Braconi, N., Kuling, L, Durlinger, B, Gual, P,. 2019. Agri-footprint 5.0, Gouda, NL.

Ruiter, T., Haffmans, S. 2021. Levenscyclusanalyse van herbruikbare en eenmalige verpakkingen. Inzicht in de milieuimpact van twaalf verschillende voedselproducten in een herbruikbare Pieter Pot verpakking versus een eenmalige verpakking. Partners for Innovation.

Speck, R, Selke, S, Auras, R, and Fitzsimmons, J. 2015. Choice of Life Cycle Assessment Software Can Impact Packaging System Decisions. Packag. Technol. Sci., 28, 579– 588. doi: 10.1002/pts.2123.

Thoden van Velzen, E. U., Jansen, M., Brouwer, M. T., Feil, A., Molenveld, K., & Pretz, T. 2017. Efficiency of recycling post-consumer plastic packages. The 32nd International Conference of the Polymer Processing Society - Conference Papers (Vol. 1914). [170002] American Institute of Physics Inc.. https://doi.org/10.1063/1.5016785

Thoden van Velzen, E. U., Smeding, I. W., & Brouwer, M. T., 2019. Verkenning effect verschuiven meetpunt recycling verpakkingen. (Wageningen Food & Biobased Research report; No. 1984). Wageningen Food & Biobased Research. https://doi.org/10.18174/503911

Thoden van Velzen, E. U. 2020. Seeking circularity: Finding sustainable packaging solutions for fresh products. (Report / Wageningen Food & Biobased Research; No. 2068). Wageningen Food & Biobased Research. https://doi.org/10.18174/526932

Thoden van Velzen, E. U., & Smeding, I. W., 2020. Potentie voor de recycling van aluminiumverpakkingen eind 2020: Studie naar de mogelijkheden voor de recycling van aluminiumverpakkingen en verwante consumentenartikelen in Nederland eind 2020. (Wageningen Food & Biobased Research report; No. 2060). Wageningen Food & Biobased Research. https://doi.org/10.18174/525699

Thoden van Velzen, E. U., & Smeding, I. W., 2022. Recycling van Nederlandse drankenkartons. (Rapport / Wageningen Food & Biobased Research; No. 2275). Wageningen Food & Biobased Research. https://doi.org/10.18174/567789

Turner DA, Williams ID, Kemp S. 2015. Greenhouse gas emission factors for recycling of source-segregated waste materials. Resources, Conservation and Recycling 105: 186–197.

Usva, K., Sinkko, T., Silvenius, F., Riipi, I., Heusala, H. 2020. "Carbon and water footprint of coffee consumed in Finland—life cycle assessment" The International Journal of Life Cycle Assessment 25: 1976–1990. DOI: 10.1007/s11367-020-01799-5

Verghese, K., Horne, R., Carre, A., 2010. "PIQET: the design and development of an online 'streamlined' LCA tool for sustainable packaging design decision support" Int J Life Cycle Assess 15:608–620 . DOI 10.1007/s11367-010-0193-2

Verghese, K., Lockrey, S., 2012. Selecting and Applying Tools. In: Verghese, K., Lewis, H., Fitzpatrick, L. (eds) Packaging for Sustainability. Springer, London. https://doi.org/10.1007/978-0-85729-988-8_7

Erwin T.H. Vink and Steve Davies 2015, Life Cycle Inventory and Impact Assessment Data for 2014 Ingeo, Polylactide Production, DOI: 10.1089/ind.2015.0003

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, [online] 21(9), pp.1218–1230. Available at: <http://link.springer.com/10.1007/s11367-016-1087-8> [Accessed February 2022]

Wikström F, Williams H, Verghese K, Clune S., 2014. The influence of packaging attributes on consumer behaviour in food-packaging life cycle assessment studies - a neglected topic. Journal of Cleaner Production 73: 100-108.

Woods, J.S., et al., 2021. A framework for the assessment of marine litter impacts in life cycle impact assessment. Ecological Indicators, 2021. **129**: p. 107918. https://doi.org/10.1016/j.ecolind.2021.107918

Annex 1 Relationship between shelf-life and food losses

Coffigniez recently summarised the various models that have been described in scientific literature about the relationship between the food loss rate and the shelf life of the products. All these models and mathematical relationships have been developed for specific food products and / or quality deterioration processes (microbial growth, oxidation, dehydration, etc.) (Coffigniez et al. 2021). These models are highly fragmented and not suited to use as a generalised relationship to approximate the effects of shelf-life changes in food loss rates. Such a generalised relationship is, however, crucial for our tool. To derive such a general relationship we analysed the food loss rate data on a product category level.

The Dutch Voedingscentrum has published the relative food loss rates in relation to the purchased amounts per category of solid and viscous liquid foods in 2019 which we combined with the average approximated shelf life of foods in these categories, see Table 1.

Table 1: The relative food loss rate in the Netherlands per category and the average estimated shelf life of each food category.

Food category	**Relative food loss rate, [%]**	**Self-estimated average shelf life per food category, [days]**
Rice	39%	365
Pasta	34%	365
Bread and bakery products	21%	7
Sauces, oils and fats	17%	84
Potatoes	14%	21
Dairy	14%	12
Candy and snacks	9%	365
Vegetables	9%	14
Fruits	8%	10
Fish	8%	5

There is no clear relationship between the relative food loss rate (FL_{exp}) of these food categories and the shelf life of these products. This was not unexpected since there are multiple reasons why food products are thrown away and not consumed. Exceedance of the best before date (EBD) is only one of the many possible causes for food waste besides: cooking too much (COO), too large portion size (POS), difficulty to completely empty the packages (EMP) and transport damage (TD). To extract the relative food loss rate that is only related to exceedance of the best-before date, first distribution coefficients for the causes of food loss per category were estimated by experts. Subsequently, the relative food loss rate per category (RFLR) was multiplied with the distribution coefficient for exceedance of the best-before date to obtain the relative food loss rate that is related to exceedance of the best-before date (RFLR EBD), see Table 2.

Table 2: Calculation of the relative food loss rates associated with the exceedance of the best-before date (FL_{exp}) per food category.

Food category	**Distribution coefficients, [%]**					**FL_{exp} [%]**
	COO	**POS**	**EDB**	**EMP**	**TD**	
Rice	98	0	1	0	1	0.4
Pasta	98	0	1	0	1	0.3
Bread and bakery products	0	49	49	0	2	10.3
Sauces, oils and fats	0	45	5	50	0	0.9
Potatoes	20	10	70	0	0	9.8
Dairy	0	0	79	20	1	11.1
Candy and snacks	0	25	70	0	5	6.3

Food category	**Distribution coefficients, [%]**					**FL_{exp} [%]**
	COO	POS	EDB	EMP	TD	
Vegetables	0	0	90	0	10	8.1
Fruits	0	0	90	0	10	7.2
Fish	0	0	90	0	10	7.2

When this relative food loss rate related to the exceedance of the best-before date (FL_{exp}) was plotted against the average estimated shelf life per food category a reasonable reciprocal relationship was found, see Figure 3.

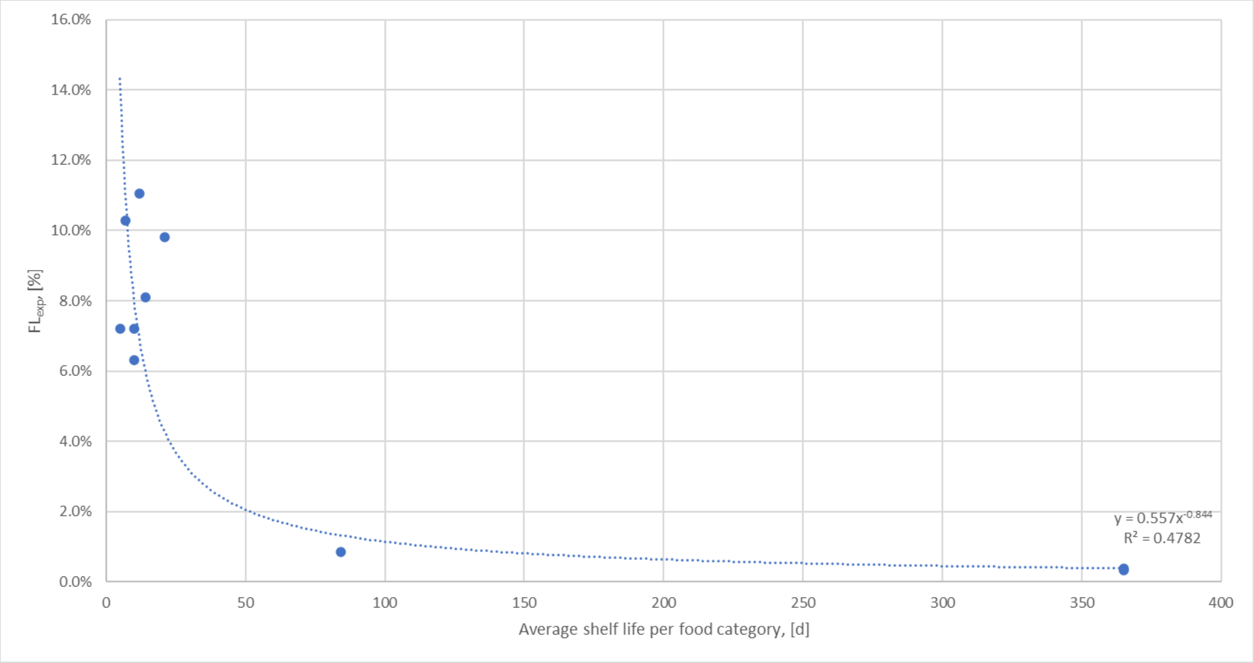

Figure 4: ***Relationship between the relative food loss rate per food category that is related to exceedance of the best before date (FL_{exp}) and the average shelf life of the food category.***

This relationship was used in the tool to estimate the effect of shelf-life changes on the food loss rate.

$$FL_{exp} = 0.557 \times SL^{-0.844}$$

Annex 2 Sources of used background data

Food product	**Source**
Roasted coffee beans	Usva, 2020
Wheat grain NL market mix	Agrifood 5 - mass allocation (Paasen et al., 2019)
Cheese, from cow milk, fresh, unripened	Ecoinvent / IPCC 2013 GWP 100a V1.03 (Wernet et al, 2016)
Lettuce (standard)	Ecoinvent / IPCC 2013 GWP 100a V1.03 (Wernet et al, 2016)
Strawberry	Ecoinvent / IPCC 2013 GWP 100a V1.03 (Wernet et al, 2016)

Materials	**Source**
All other materials in database / used in cases	Ecoinvent / IPCC 2013 GWP 100a V1.03 (Wernet et al, 2016)
PLA	Vink and Davies, 2015
Starch/biobased PBS	Broeren, 2017
Recycled steel	Turner, 2015
Adhesive	Own estimate based on proxy
EVOH	Ethylene vinyl acetate copolymer (from Ecoinvent / IPCC 2013 GWP 100a V1.03) as proxy
Rice paddy straw pulp	Own calculation, case : “Strawberry packaging”

Production processes	**Source**
All other production processes in database / used in cases	Ecoinvent / IPCC 2013 GWP 100a V1.03 (Wernet et al, 2016)
Pulp moulding in Malaysia	Own calculation, see case report Strawberry packaging
Pulp moulding in the Netherlands	Own calculation, see case report Strawberry packaging

End-of life (EOL) processes	**Source**
All other EOL processes in database / used in cases	Ecoinvent / IPCC 2013 GWP 100a V1.03 (Wernet et al, 2016)
Incineration processes of plastic types	Stoichiometric calculation
Incineration of paper/cardboard	Own estimate
Composting processes of composable polymers	European Commission, 2018
Recycling of PE, PP, PET, paper/cardboard, steel, aluminium, cotton and mixed waste	Turner, 2015
Recycling of other materials	Proxys based on Turner, 2015

Reuse processes	**Source**
All data	Ecoinvent / IPCC 2013 GWP 100a V1.03 (Wernet et al, 2016)

Transport	**Source**
Diesel	https://www.co2emissiefactoren.nl/ Last accessed august 2022
Consumption of diesel per km of an average truck and light commercial vehicle	Ruiter & Haffmans, 2021
Consumption of diesel per km of a waste collection truck	Average from Nguyen, 2010

Recycling processes / efficiencies	
All data	Background knowledge of researchers of WFBR based on previous projects, such as: (Brouwer et al. 2017 and 2019; Thoden van Velzen 2017, 2019, 2020, 2022)

To explore
the potential
of nature to
improve the
quality of life

Wageningen Food & Biobased Research
Bornse Weilanden 9
6708 WG Wageningen
The Netherlands
E info.wfbr@wur.nl
wur.nl/wfbr

Report 2442

The mission of Wageningen University & Research is “To explore the potential of nature to improve the quality of life”. Under the banner Wageningen University & Research, Wageningen University and the specialised research institutes of the Wageningen Research Foundation have joined forces in contributing to finding solutions to important questions in the domain of healthy food and living environment. With its roughly 30 branches, 7,200 employees (6,400 fte) and 13,200 students and over 150,000 participants to WUR’s Life Long Learning, Wageningen University & Research is one of the leading organisations in its domain. The unique Wageningen approach lies in its integrated approach to issues and the collaboration between different disciplines.