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

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ABSTRACT

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

## 1. Introduction

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

### *1.1. Bacon*

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

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### 1.2. Packaging for bacon

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

### 1.3. Packaging sustainability

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

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

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

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

### 1.4. Literature overview

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

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

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

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

### 1.5. Goal and research question

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

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

## 2. Packaging systems

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

### 2.1. Thermoformed films

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

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

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

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

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

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

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

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

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

### 2.2. Vacuum bag

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

### 2.3. Shrink bag

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

#### 2.3.1. Medium abuse barrier shrink bag (3a)

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

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

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

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

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

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

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

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

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

## 3. Methods

### 3.1. *Life cycle assessment*

#### 3.1.1. *Calculation procedure*

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

#### 3.1.2. *Functional unit*

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

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

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

#### 3.1.3. *Environmental impact categories*

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

#### 3.1.4. *Scenario and sensitivity analysis*

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

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

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

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

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

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

**Table 8**
Scenario analysis.

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

### 3.2. Circularity

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

#### 3.2.1. Recyclability assessment

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

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

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

### 3.3. Share of renewable energy sources

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

### 3.4. Food-to-packaging ratio for environmental impacts

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

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

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

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

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

## 4. Results

### 4.1. Environmental impacts of the examined packaging

#### 4.1.1. Results for the six variants

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

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

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

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

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

#### 4.1.2. Recycling scenarios (1b)

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

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

#### 4.1.3. Sensitivity analysis

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

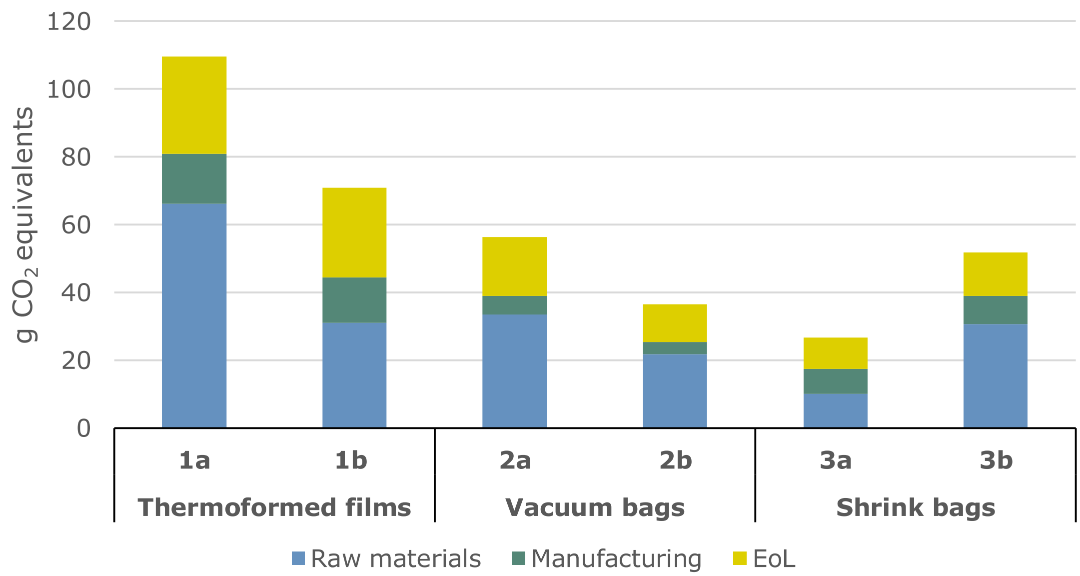


**Fig. 1.** Climate change results.

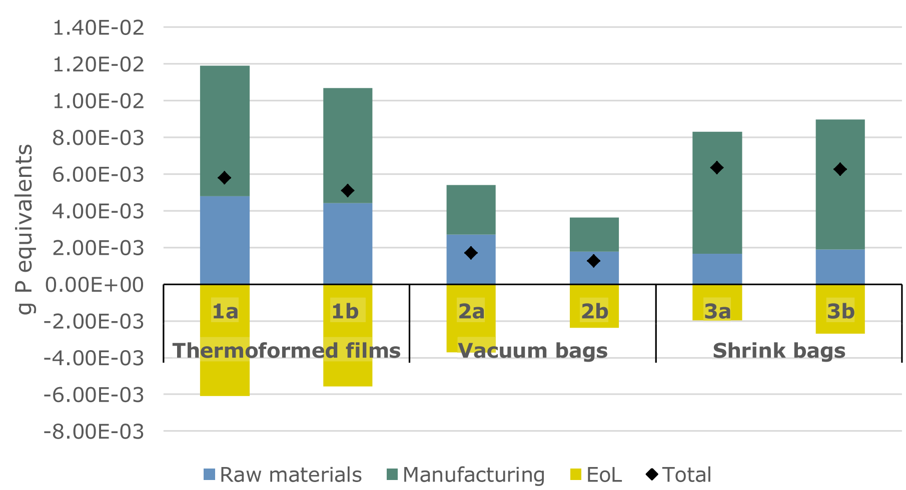


**Fig. 2.** Freshwater eutrophication results.

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

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

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

## 4.2. Circularity

### 4.2.1. Recyclability

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

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

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

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

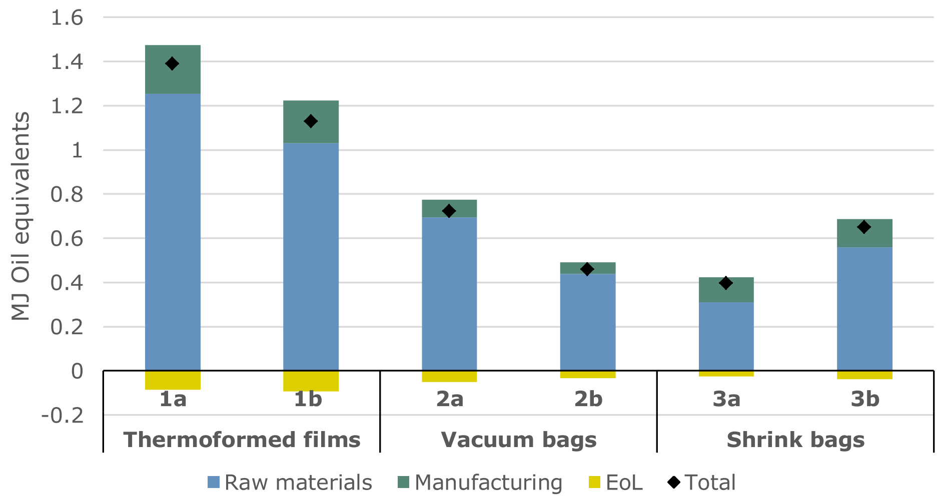


**Fig. 3.** Fossil resources results.

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

#### *4.2.2. Share of renewable energy sources*

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

### *4.3. Food to packaging ratio*

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

## 5. Discussion

### *5.1. Environmental impacts of the examined packaging*

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

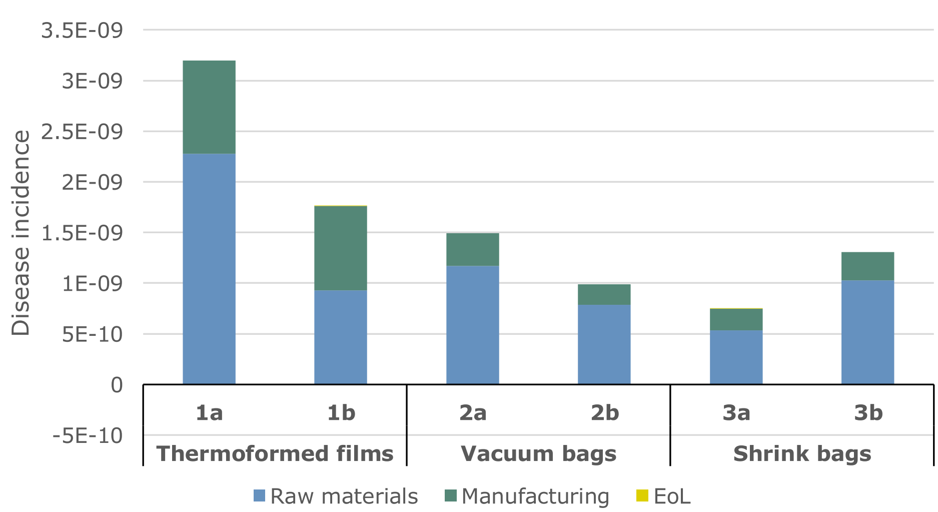


**Fig. 4.** Respiratory effects results.

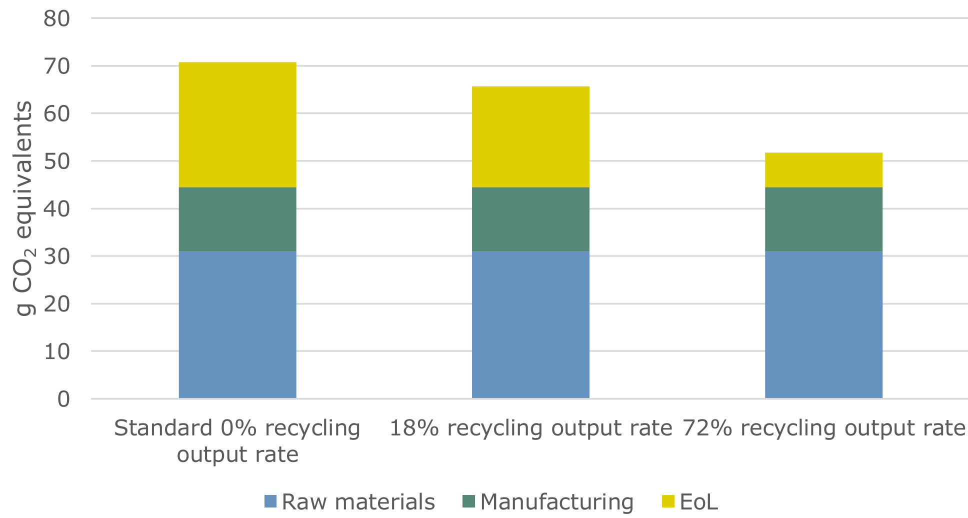


**Fig. 5.** Climate change results for three recycling scenarios (1b).

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

*5.1.1. Main drivers for environmental impacts*

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

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

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

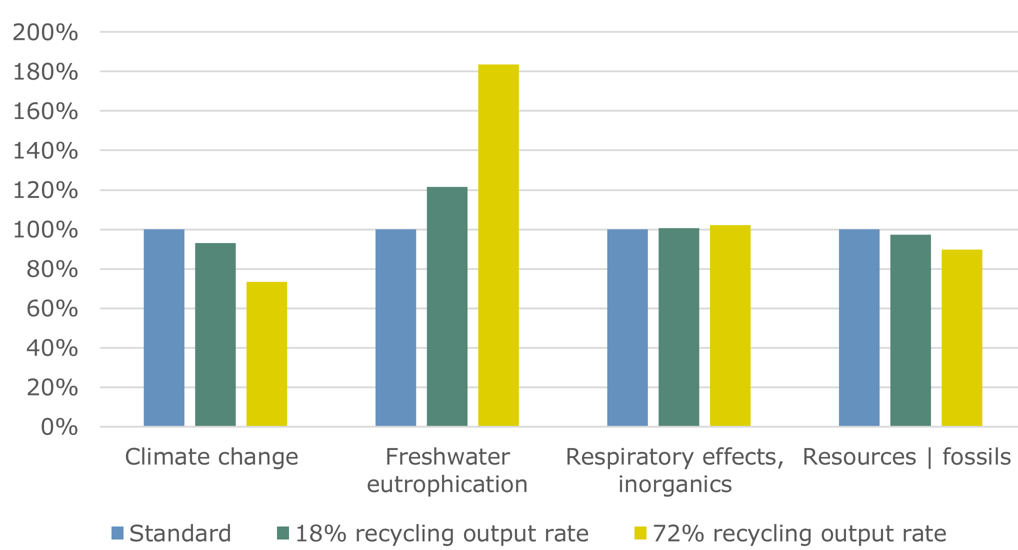


**Fig. 6.** All impact categories for three recycling scenarios (1b).

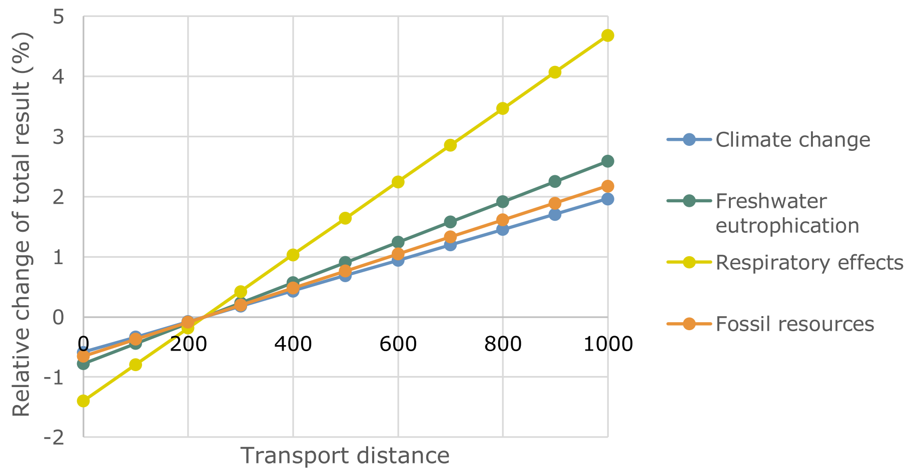


**Fig. 7.** Sensitivity analysis for transport distance (averaged for all variants).

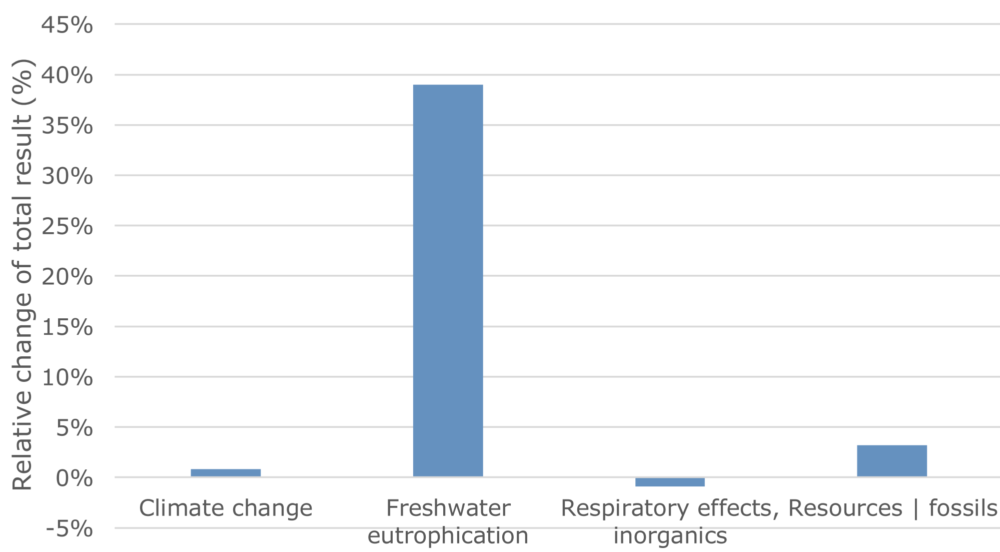


**Fig. 8.** Sensitivity analysis - LDPE instead of LLDPE (all variants).

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

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

### 5.1.2. *Sensitivity and scenario analyses*

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

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

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

The energy consumption for shrinking the films has a relevant

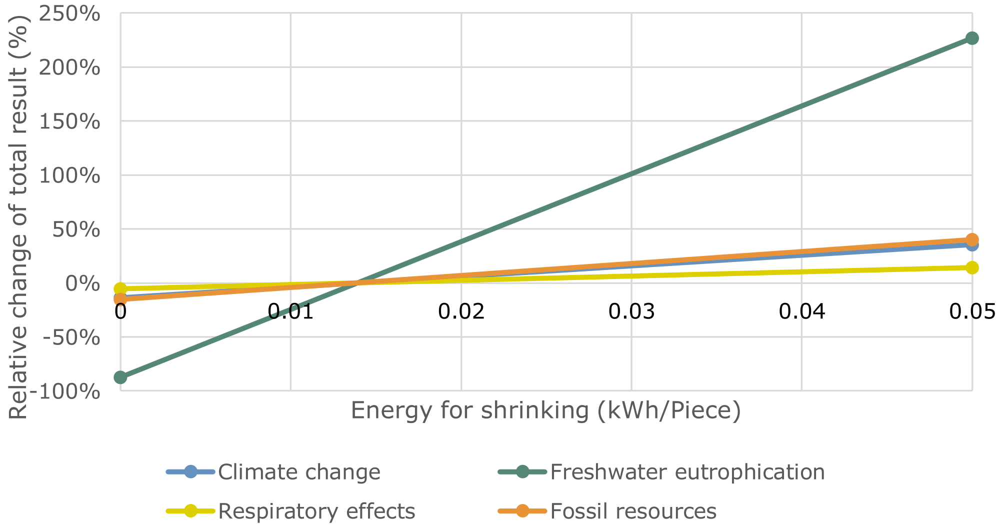


**Fig. 9.** Sensitivity analysis for heat shrinking – influence of assumptions for energy demand on total result (3a + 3b).

**Table 10**
Results of the recyclability assessment (RecyClass).

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

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

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

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

### *5.2. Circularity*

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

#### *5.2.1. Recyclability issues*

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

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

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

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

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

#### 5.2.2. Use of recycled material

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

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

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

#### 5.2.3. Renewable energy sources

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

#### 5.2.4. Biobased and compostable polymers for meat packaging

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

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

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

#### 5.2.5. Other circularity aspects

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

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

#### 5.2.6. Conclusion for circularity

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

### 5.3. Food-to-packaging ratio

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

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

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

## 6. Conclusion

### 6.1. Main findings

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

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

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

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

### 6.2. Limitations

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

### 6.3. Recommendations & outlook

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

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

## Author statement

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

## Declaration of competing interest

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

## Appendix A. Supplementary data

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

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