Circular Economy & Environment
Princetonlaan 6
3584 CB Utrecht
P.O. Box 80015
3508 TA Utrecht
The Netherlands

www.tno.nl

T +31 88 866 42 56

TNO report Internal

TNO 2022 R11604

Comparative environmental life cycle assessment of PET/LDPE, MONO PET and MONO PE films

Date	21-09-2022
Author(s)	Dr. Golkaram, M., Heemskerk, L.P.
Number of pages	49 (incl. appendices)
Number of appendices	4
Sponsor	BOPET Films Europe
Project name	LCA mixed plastics Bopet
Project number	060.49664

Executive Summary

The objective of this study is to perform a comparative LCA of the conventional multilayer packaging for dry foods as the reference (e.g., muesli), composed of PET/LDPE, and two alternatives composed of mono-materials, namely MONO PET and MONO PE laminate films. The two alternative solutions are made from mainly PE and PET which improves their recyclability. The aim is to understand the differences in environmental impact, particularly concerning the global warming potential (GWP) in CO_2-eq.

A cradle-to-grave assessment excluding the printing, filling and use phase of the packaging film assessed the three different scenarios: 1) State-of-the-Art, 2) Future without recycling, 3) Future with 69% recycling. In all three scenarios, the LCA proved the environmental benefits of using MONO PET laminate film in comparison to the reference film of PET/LDPE. The MONO PE laminate film showed, in all scenarios, to have a higher environmental impact compared to the reference of PET/LDPE. The low environmental impact of MONO PET is due the lower thickness and thus weight (30.74g for MONO PET, 38.84g for PET/LDPE, and 50.21g for MONO PE) and higher recycled content of the films (50% recycled PET).

This benefit for MONO PET can be increased if the collection and sorting infrastructure is improved. Currently packaging films smaller than A4, although collected, are often not sorted to a DKR-fraction1 (quality specification) for recycling in Europe. This leads to limitations for the recyclability of the newly designed films. The benefits of recyclability, for mono-material films (MONO PET and MONO PE) can be seen when at least 69%, derived from literature (Antonopoulos et al. 2021), of the films are collected and sorted. However, for MONO PE the environmental impact in the 69% recycling scenario will still not be lower than the reference PET/LDPE film with the same recycling rate.

For the PET/LDPE pyrolysis, in this study it is assumed that the PET/LDPE films are mixed with polyolefins and are in low concentration to avoid efficiency challenges or high acid content in the reactor due to the oxygen levels of PET that may occur during pyrolysis process. (Kusenberg et al. 2022).

For the specific application of dry food (muesli) packaging the MONO PE films do not show an environmental impact improvement compared to PET/LDPE films due to the importance of stiffness of the pouch and thus a higher required thickness. The thickness of the films and their functionality has a critical role in the environmental performance. The use of thin film in addition to recycled fraction (50%) for PET can improve the results significantly.

A sensitivity analysis was conducted to assess the GWP impact of full recyclability (100% recycling rate) of the films, excluding disposal during and following the collection stage. The difference between sensitivity analysis 1: state-of-the-art (SoA) and sensitivity analysis 2: future, corresponds to the electricity grid mix used in the recycling and processing of the films as well as the technology development level (efficiency).

[1] Deutsche Gesellschaft für Kunststoff Recycling

When reaching a hypothetical 100% recycling rate for packaging films, 36%, 40% and 30% reductions in global warming potential (GWP) are observed for MONO PE, MONO PET and PET/LDPE, respectively. The reduction is even higher for the future scenario where renewable electricity is used for the recycling (mechanical, pyrolysis and glycolysis); 41% for MONO PE, 75% for MONO PET and 36% for PET/LDPE films, respectively.

The impact assessment of pyrolysis however involves many assumptions. In reality, the results highly depend on the type, scale and pyrolysis condition which leads to a different mix of products. The same applies to glycolysis. These technologies have a low technological readiness level (low TRL), requiring further development and therefore, the generated results can only be indicative of the technologies as they are applied in this study. It is recommended to treat the outcome of the study with care. Similarly, the functionality of the films depends on the application of the films and by changing the thickness, where for instance modulus is less relevant, different results may be obtained.

Contents

Index of figures

Index of tables

1 Introduction

1.1 General background on multilayer packaging

Flexible plastic packaging is widely used in the storage and packaging of consumer products, such as chemicals, food and beverages (Veksha et al. 2020). Depending on the application, multilayer (ML) packaging is comprised of many layers such as polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET) and a variety of different barrier layers such as AlOx or ethylene vinyl alcohol (EVOH) copolymer.

Moreover, packaging can be further modified with additives, such as fillers, plasticizers, flame retardants, colorants, stabilizers, lubricants, foaming agents and antistatic agents (Groh et al. 2019). Because of this diversity in material composition and mechanical recycling of ML packaging waste stays technically challenging. Design for recycling (DFR), ensuring films are designed in such a way that recycling is easier or an option at all, is considered to facilitate the reprocessing of the waste ML packaging (Siracusa et al. 2014). This follows the recommendations of the Ellen MacArthur Foundation and Milliken's Zero Waste Hierarchy which can be seen in Figure 1 (Billiet and Trenor 2020).

Figure 1. Milliken's hierarchy for EoL preference in a circular economy (Billiet and Trenor 2020).

In order to improve the recycling rate, the use of mono-materials is attractive. For instance, bi-axially oriented plastic films composed of PE (MONO PE) or PET (MONO PET) are introduced by Dow, SABIC and DuPont (Dow 2018; SABIC 2021). As per industry standard these mono-material films are composed of maximum 5% other material than the core polymer. These films with high tensile strength, good transparency, high puncture and impact resistance can be used for food packaging and other applications to replace multi-material films (Ren et al. 2020).

A scenario analysis done by Antonopoulos et al. has shown that, to achieve a recycling rate of 49% (here recycling rate includes the collection, sorting and recycling efficiencies), all of the best practices need to be implemented, while to fulfil the ambitious recycling targets set at EU27 level (55% overall recycling rate), even further improvements are required (Antonopoulos et al. 2021).

Thus, the use of mono-material alternatives can be promising to improve the recycling rate and lower the environmental impacts of packaging films. The emphasis is in particular on the printed mono-material, as it has been shown that even a metalized bi-axially oriented polypropylene (BOPP) with a thin layer of aluminium leads to nonrecyclable material (Rodrigues et al. 2020). Although the aluminium fraction is easily separable through chemical recycling. In this context, the Life Cycle Assessment (LCA) methodology can be used to assess and compare the environmental impact of technical solutions (Siracusa et al. 2014, 2011a, 2011b). Recently, Maga et al. carried out an LCA and showed that the mono-material solutions have the lowest environmental impact across major impact categories while multilayer products exhibit the highest environmental impacts (Maga et al. 2019).

Specifically in this context and LCA, a comparison will be made between the reference product PET/LDPE films and BOPET and BOPET film alternatives. See next chapter for more details.

1.2 LCA context

For conducting the comparative LCA the ISO standard 14040 and ISO 14044 is used as the framework for conducting the LCA. This standard clearly illustrates the steps required in the LCA. Figure 2 visualises these steps necessary for an LCA study. The goal and scope part describes the products under study, functional unit (FU), system boundary and allocation method while inventory analysis corresponds to the complete sets of data collected for the impact assessment. Impact assessment is the stage before interpretation whereby the environmental impact through various impact categories is estimated and interpreted in the final stage (life cycle interpretation).

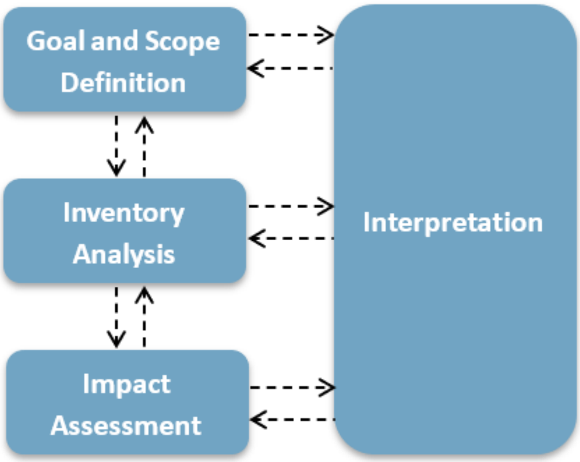

Figure 2. ISO 14044 framework for LCA study.

2 Goal and scope definition

2.1 Goal of the study

2.1.1 Reasons for carrying out the study

This comparative LCA on film packaging is aimed to assess the environmental impact of mono-material films (specifically MONO PET) compared to the existing PET/PE laminates, particularly focussing on the global warming potential (GWP) in CO_2-eq. The target application is film packaging of dried foods such as muesli. The main function of the polyester film today is to make the package stiff enough and allow fast sealing cycles in the manufacturing of the film packaging due to the high temperature resistance of the polyester.

2.1.2 Intended audience

This report is aimed for internal use by the BOPET films Europe consortium including DuPont Teijin Films, Polyplex, Mitsubishi polyester films and TPL. This means results can be shared in the company with clients and business partners. If results are to be published to a wider audience, via website or conference, TNO requests approval (see TNO terms and conditions).

2.2 Scope of the study

2.2.1 Function, functional unit and reference flows

The functional unit defines the quantification of the identified functions of the product (ISO 2018). Its primary purpose is to provide a reference to which the inputs and outputs are related to ensure comparability of LCA results. This is especially important when different systems are being assessed, to ensure that such comparisons are made on a common basis.

The functional unit for the product under study is: 1 piece of packaging film for food (muesli) packaging application with the surface area of 500 cm^2.

The reference product selected for comparison is PET/LDPE film presently sold in the market (Table 1). The proposed solutions are mono-material PET and PE based films including barrier layers. The thickness and the composition of films are designed and thoroughly tested by industry (including BOPET films Europe) to provide equal functionality in terms of stiffness and barrier properties. As such different properties of the packaging film for food, e.g., stiffness, toughness and durability, are including in the study.

2.2.2 Product system to be studied

The following three types of film are studied (Table 1)

- **Existing design: PET/LDPE laminate** structure PET 12 µm -1.4 g/cm^3 **-** AlOx coated - front printed / 2 µm glue / 60 µm sealable PE.
- **MONO PET solution**, BOPET 12 µm -1.4 g/cm^3 reverse printed /2 µm glue)/ 30 µm Sealable BOPET film 1.39 g/cm^3 AlOx coated on outer side. PET film in 1 contains 50 % mechanically recycled PCR PET.
- **MONO PE solution**, BOPE 25 µm 0.97 g/cm3 reverse printed /2 µm glue/ 80 µm LDPE 0.94 g/cm^3 (film with 48 µm PE sealing layer/ 4 µm tie layer/4 µm EVOH layer / 4 µm tie layer/20 µm LDPE cover).

Table 1. Thickness (µm) of the layers for each of the packaging types.

se case	Total	rPET	PET	LLDPE	LDPE	EVOH	Glue (ethylene vinyl acetate)	Tie layer (ethylene vinyl acetate)	AlOx
PET/LDPE	76	6	6	60			2		20 (nm)
BOPET	44	21	21				2		20 (nm)
BOPE	103			25	68	4	2	4	

2.2.3 *Geographical scope of the study*

The study is conducted for the geography of Europe.

2.2.4 *System description & boundary*

The system boundary determines which common unit processes are included in the LCA. The selection of the system boundary is consistent with the goal of the study. The system illustrated in Figure 2, includes the raw materials extraction & production (incl. transport), the film packaging manufacturing and end-of-life scenarios.

For the film packaging manufacturing, the processes differ per type of film. For PET/LDPE the production includes the plastic extrusion process, followed by metallization and finally lamination. Specific for MONO PE and MONO PET films is the biaxial orientation process (Chen et al. 2020)

Waste cuttings resulting from the lamination stage during product manufacturing are treated through incineration (with energy recovery), landfill and recycling.

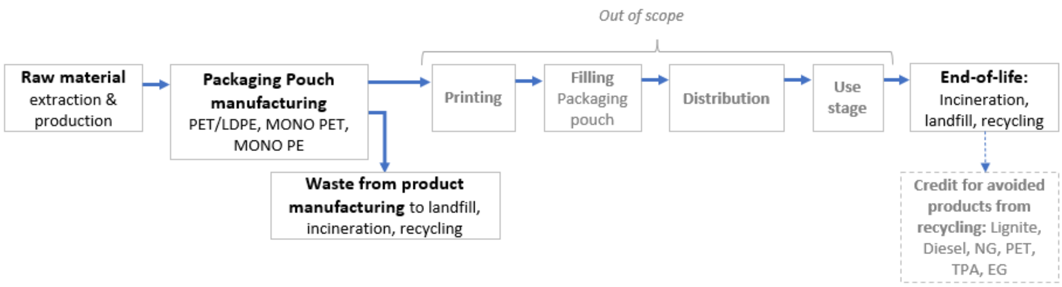

Figure 3. Illustration of the system boundary used in LCA.

At the end-of-life (EoL) the film packaging is treated through incineration (with energy recovery), landfill and recycling. In section 2.2.5 specifics are provided for the different EoL scenarios. A credit is given to the formed products resulting from the mechanical and chemical recycling (pyrolysis and glycolysis).

Out of scope for this LCA are the printing, filling of the film packaging with dry food (e.g., muesli), the distribution and the use stage of the products. The impact of filling of the packaging with products are not the same for all three packing methods, as the packing process will be significantly less efficient due to the need to run at lower sealing temperatures because of the inherent properties of the mono-PE structure.

The filling is however not in the scope dure to complexity and lack of data availability. The other phases, printing, distribution and use phase also excluded for complexity and lack of data reasons.

The LCA was carried out at a cradle-to-grave level. The material flow is shown in Table A.1 in the Appendix. The films are produced and then, after use, are disposed and collected according to their specific EoL collection statistics (Table 3). The study is aimed for the European geography using two periods of 2021-2022 and 2050.

2.2.5 *Scenarios*

In order to give an insight into the impact of proposed mono-material films in different periods it is important to include the changes in recycling rate and electricity grid mix in addition to the development in the technologies of recycling (Table 3).
For this purpose, two perspectives are analysed:

- **State of the art (SoA):** the avoided energy from incineration with energy recovery will be according to the 2021 energy mix in Europe. Sorting and collection of films is done according to state-of-the-art data; they are collected and sorted with other A4-sized films[2] and are sent to incineration. Chemical recycling, as it is still in development, will by assumed suboptimal as improvements are still to be done in the future. The recycled content of PET comes from mechanically recycled PET.
- **Future:** the avoided energy from incineration with energy recovery will be according to the 2050 energy mix in Europe. Sorting and collecting is assumed optimized to the recycling technology. Chemical recycling, as it is assumed to be on the market, is assumed more optimized. The recycled content of PET comes from chemical recycling of PET.

Furthermore, sensitivity analysis is carried out to determine the extent of the effect of recycling excluding the disposal of the waste. Table 2 list the scenarios and the sensitivity analyses conducted in this study. In the first two scenarios, all the films are disposed through incineration with energy recovery, while in the third scenario a large fraction is recycled. The 69% recycling is derived from literature (Antonopoulos et al. 2021) by which the recycling rate of the films in Europe in the future is predicted (Table 3). The sensitivity analysis is carried out to investigate the impact of full recyclability (100% recycling rate) of the films, excluding disposal during the collection stage.

Table 2. Scenarios and sensitivity analysis conducted in this study.

Scenario	Scenario definition
1	SoA (Incineration with energy recovery, landfill)
2	Future (Incineration with energy recovery, landfill)
3	Future (Incineration with energy recovery, landfill, and chemical recycling)
Sensitivity 1	All chemical SoA
Sensitivity 2	All chemical future

[2] The A4 size is a rule of thumb in industry which is the standard size above which the films are sorted. Smaller films are not economically reasonable to be recycled at the moment.

For chemical recycling, different technologies are chosen depending on the polymer type. This is pyrolysis for the films containing polyolefins (MONO PE and PET/LDPE) and glycolysis for MONO PET.

- **Glycolysis:** is a chemical recycling technology, whereby ethylene glycol is added to specific condensation polymers (e.g., PET, Nylon 6) in the presence of a catalyst. Thus, the polymer is depolymerized to its building blocks, which can be re-used in making new polymers (Schwarz et al. 2021)[3]. For the depolymerization process, polymer is first shredded and then at 190°C using acid or basic catalysts, forms the polymers' monomer.
- **Pyrolysis:** is a (thermo-)chemical recycling method to recycle plastics and other organic materials. Plastic is first heated in the absence of oxygen to thermally degrade to shorter carbon. Pyrolysis technologies include fixed- and fluidized-bed, microwave or conical spouted bed reactors. After the pyrolysis depending on the pyrolysis parameters, three fractions of solid, liquid and gas phase are produced which are separated afterwards. The solid part (char) is usually used for energy recovery while the liquid part (pyrolysis oil) is further cracked to produce valuable products such as monomers and other organic materials. The gas phase (pyrolysis gas) is usually combusted internally to provide additional energy for the pyrolysis process. (Schwarz et al. 2021).

In this study it is assumed that the PET/LDPE films are mixed with polyolefins and are in low concentration to avoid challenges during pyrolysis process. In reality such low concentrations do not interfere with the pyrolysis process.

Table 3. EoL statistics for packaging films. Data derived from literature (Antonopoulos et al. 2021).

Scenario	Year	Electricity grid mix	Incineration	Landfill	Recycling
1	2021	2021	53%	47%	0
2	2050	2050	90%	10%	0
3	2050	2050	28%	3%	69%
Sensitivity 1	2021	2021	0	0	100%
Sensitivity 2	2050	2050	0	0	100%

2.2.6 *Life cycle impact assessment (LCIA) methodology and types of impact*

The indicators and their units used in this report are shown in Table 4 and Table 5. Each of the impact assessment methods, reflect on one individual environmental aspect. Climate change is probably the most relevant impact category and the characterization factors come from the IPCC (Inter-governmental Panel on Climate Change), IPCC 2013 GWP 100a version 1.03. In addition, ReCiPe 2016 midpoint (H) is chosen to indicate the impacts in other categories listed in Table 4.[4] A full description of the impact categories is provided in the Appendix (Huijbregts et al. 2017).

---

[3] A worst-case scenario cobalt catalyst was used in this case.
[4] The ReCiPe 2016 midpoint (H) is an internationally common and well-accepted in industry method. TNO has large experience with implementing and interpreting the ReCiPe 2016 method.

Table 4. The 18 environmental impacts considered in the ReCiPe 2016 database method at the midpoint level (H) (Huijbregts et al. 2017; Catalán et al. 2019).

Impact Category	Unit
Global warming (GWP)	kg CO_{2eq}
Stratospheric ozone depletion (ODP)	kg $CFC^{-11}{}_{eq}$
Ionizing radiation (IRP)	kBq Co-60_{eq}
Ozone formation, human health (HOFP)	kg NOx_{eq}
Fine particulate matter formation (FPMF)	kg $PM2.5_{eq}$
Ozone formation, terrestrial ecosystems (EOFP)	kg NOx_{eq}
Terrestrial acidification (TAP)	kg SO_2
Freshwater eutrophication (FEP)	kg P_{eq}
Marine eutrophication (MEP)	kg N_{eq}
Terrestrial ecotoxicity (TETP)	kg 1.4-DCB
Freshwater ecotoxicity (FETP)	kg 1.4-DCB
Marine ecotoxicity (METP)	kg 1.4-DCB
Human carcinogenic toxicity (HTPc)	kg 1.4-DCB
Human non-carcinogenic toxicity (HTPnc)	kg 1.4-DCB
Land use (LOP)	m^2 year
Mineral resource scarcity (SOP)	kg Cu_{eq}
Fossil resource scarcity (FFP)	kg oil_{eq}
Water consumption (WCP)	m^3

Table 5. The environmental impacts considered in IPCC 2013 GWP 100a version 1.03.

Impact Category	Unit
Global warming (GWP)	kg CO_{2eq}

2.2.7 *Data requirements*

The data on the choices of the use case and the proposed solutions were provided by the BOPET Films Europe consortium (DuPont Teijin Films, Polyplex, Mitsubishi polyester films, TPL). In addition to the primary data, literature was used to complement the life cycle inventory (LCI) for the chemical recycling (glycolysis (Schwarz et al. 2021) and pyrolysis (Sivagami et al. 2021; Russ et al. 2020)) and EoL statistics (Antonopoulos et al. 2021).

2.2.8 *Assumptions*

Several assumptions were made which can be seen in Table 6. Attention was paid to specifying these assumptions to avoid unrealistic assumptions which can affect the result. For instance, according to the literature, currently char fraction of pyrolysis does not have a mature value chain (Russ et al. 2020) and we assumed this will change in the future. Thus, in the current scenario it is sent to landfill.

Pyrolysis oil quality is assumed to be only based on lower heating value (LHV) since it is assumed that the product is used for combustion.
Otherwise, the carbon amount is a decisive factor in the quality of the oil and should be included in the model.

Table 6 refers to the yield and carbon efficiency for glycolysis and pyrolysis, respectively.
Yield is defined as the ratio (in weight) of PET which is depolymerized through glycolysis and the entire PET which is fed into the process.

Therefore, a fraction of the PET is not depolymerized and is send to incineration due to process inefficiency. Carbon efficiency is defined as the oil (liquid) fraction of the pyrolysis which is produced as the output.

For the avoided products of glycolysis for the SoA it is assumed that TPA is avoided. Actually, the product is BHET, however, due to lack of data on BHET, TPA is used as a proxy. For the future scenario, it is assumed that BHET is produced and directly polymerized, yielding EG and PET.

Table 6. Assumption made in this study.

Scenario		Avoided products	Electricity grid mix	Other assumptions
Glycolysis				
SoA	Yield=0.7	Avoids TPA	Electricity and heat current	
Future	Yield=0.9	Avoids PET (in efficient polymerization process of evolved in industry) and EG	Electricity and heat future	The electricity for production is also future grid
Pyrolysis				
SoA	Carbon eff. (%) 30 (PET/LDPE) and 58 (MONO PE)	Char landfill	Electricity and heat current	Material efficiency = 90%
Future	Carbon eff. (%) 30 (PET/LDPE) and 58 (MONO PE)	Char avoids lignite	Electricity and heat future	Material efficiency = 100%

2.2.9 *Limitations*

The results provide the reader with detailed assessment of the impact of redesign for the plastic films. Since the impact of littering is not considered, the corresponding effect in ReCiPe mid-point impact categories are excluded. In reality, this should be corrected by further research.

2.2.10 *Third party review*

A critical review, according to ISO 140444:2006 on the methodology and outcomes of this LCA study was performed by a single independent external expert, from EcoChain. A report and statement of the review conducted is provided in appendix 4.

3 Life Cycle Inventory Analysis

Life cycle inventory analysis (LCIA) involves the collection of data and the calculation procedures to quantify relevant inflows and outflows of a product system. The definition of the goal and scope of the study provides the initial plan for conducting the life cycle inventory analysis. As outlined in ISO standard 14040/14044 the operational steps follow preparation for data collection, data collection, data validation, relating data to unit processes and functional unit, data aggregation, and refining system boundary.

3.1 Data collection and calculation

3.1.1 Production

The production and composition of each of the films differs. Table 7 shows the inventory for the materials required per film (per FU). This primary data is provided by the BOPET films Europe consortium. This consortium consists of different companies including Dupont Teijin Films, TPL, Polyplex and Mitsubishi polyester films.

Different layers provide different functionalities in the ML films. The AlOx and EVOH are necessary for the barrier properties and glue to stick the layers to each other. Moreover, PET is assumed to be 50% from recycled material. For the scenario 1 and sensitivity analysis 1 where the SoA is used, we assume the recycled PET comes from mechanically recycled PET while for other scenarios (future) it is reasonable to assume the recycled content originates from chemically recycled PET through glycolysis.

Table 7. Datasets for the materials in grams required per FU.

PET/LDPE	
Entry	**Amount**
LDPE	29.10
PET	4.20
rPET	4.20
Glue	1.30
AlOx	0.04
Total	**38.84**
MONO PET	
Entry	**Amount**
rPET	14.70
PET	14.70
Glue (ethylene vinyl acetate)	1.30
AlOx	0.04
Total	**30.74**
MONO PE	
Entry	**Amount**
LLDPE	12.13
LDPE	23.28
LDPE	9.70
EVOH	1.90
Glue (ethylene vinyl acetate)	1.30
tie layer (ethylene vinyl acetate)	1.90
Total	**50.20**

Table 8 shows the processes required for the manufacturing of each film. PET/LDPE film is made using extruded PET and its metalizing and lamination with LDPE. For the MONO PET, similarly extrusion, metalizing and lamination is needed, while MONO PE uses a co-extrusion for the processing of the different layers.

Table 8. Dataset for the processing of the films per FU.

PET/LDPE			
Process	**Entry**	**Amount**	**Unit**
Extrusion	Extrusion, plastic film	39.79	grams
Metalizing (Bayus 2015)	Electricity	0.009	MJ
	Boron Nitride	5.60E-10	grams
	Titanium diboride	5.60E-10	grams
Lamination**	Extrusion, plastic film	38.84	grams
MONO PET			
Process	**Entry**	**Amount**	**Unit**
Extrusion**	Extrusion, plastic film	30.74	grams
Metalizing (Bayus 2015)	Electricity	0.009	MJ
	Boron Nitride	5.60E-10	grams
	Titanium diboride	5.60E-10	grams
MONO PE			
Process	**Entry**	**Amount**	**Unit**
Co-extrusion**	Extrusion, co-extrusion	51.44	grams

*The lamination process uses extrusion as a proxy, but the electricity consumption is corrected for lamination process.
**Biaxial orientation takes place during the extrusion with negligible required electricity

To produce the rPET two datasets are used. For the state-of-the-art (SoA) scenario the mechanical recycling is used to produce the recyclates based on a USLCI dataset (see appendix 2). For the future scenario the recyclates are produced via glycolysis, thus, an Ecoinvent dataset is used as a unit process, since the USLCI dataset is a system process. Then, the Ecoinvent process *Polyethylene terephthalate, granulate, amorphous {RER}| production | APOS, U* is modified by replacing the monomer production burden by the burden of glycolysis for the same monomers (appendix 2).

3.1.2 *Collection and sorting*

The collection and sorting steps were based on USLCI dataset and updated for European geography by changing the distances and electricity grid (see appendix 2). The electricity grid used in the sorting and collection is based on an Ecoinvent dataset. For the sake of consistency, the updated electricity is only used for MONO PET specific processes, such as processing and recycling technologies while all the default processes in the production of the upstream materials and the sorting step is based on Ecoinvent. This decision is made as the processing and end of life recycling technologies were the focus of the study and other steps are common for all use cases/scenarios. Furthermore, since the reference for used volume of fuel as the input, instead of energy (MJ or kWh) for reporting the heat consumption, USLCI was chosen for consistent allocation (Diesel, combusted in industrial boiler/US, Natural gas, combusted in industrial boiler/US, Liquefied petroleum gas, combusted in industrial boiler/US).

3.1.3 *EoL (recycling and disposal burden and the avoided products)*

The glycolysis process for MONO PET is modelled using literature data (Schwarz et al. 2021). The product of the glycolysis process is bis(2-Hydroxyethyl) terephthalate (BHET). But this depends on the technology as well, for instance some technologies go back to PTA and EG. However, due to lack of the LCI for this compound, terephthalic acid (TPA) is used as a proxy for the current scenario, while for the future scenario it is assumed that BHET is repolymerized and ethylene glycol (EG) and PET is produced as the final products. These two routes although are assumptions, give a range of minimum and maximum credit to the glycolysis product (Table 9). For the transportation, a distance of 300 km is assumed. The transportation of the materials required for the glycolysis, an Ecoinvent market process is chosen, in which the average distance is included.

Table 9. Unit process for the glycolysis process of MONO PET (per kg input PET).

Entry	Amount	Unit
Inputs		
Ethylene glycol	0.30	kg
Cobalt (acetate)	0.03	kg
Soap	0.01	kg
Water	3.90	kg
Electricity	0.02	kWh
Transportation	0.30	tkm
Outputs		
Wastewater	3.90	kg
TPA (current scenario)	0.91	kg
PET (future scenario)	0.89	kg
EG (future scenario)	0.29	kg

For MONO PE and PET/LDPE, the pyrolysis is modelled using literature data (Sivagami et al. 2021; Russ et al. 2020) as can be seen in Table 10. For pyrolysis additional sorting is necessary as pyrolysis requires clean streams without sulphur, oxygen or nitrogen containing compounds (Russ et al. 2020). The output of the pyrolysis depends on the input composition and is based on plant scale experiments from literature (Sivagami et al. 2021). For the current scenario it is assumed that the solid fractions (char) end up in the landfill as there is not a mature value chain to use these fractions. For the future scenario, this fraction replaces lignite. The liquid fraction (pyrolysis oil) replaces diesel normalized to have equivalent LHV, while the gas phase replaces natural gas:

$$Replaced\ Diesel\ (kg) = pyrolysis\ oil\ fraction\ (kg) \times \frac{LHV_{plastic}}{LHV_{Diesel}} \quad (1)$$

For more detailed calculations see Appendix.

Table 10. Unit process for the pyrolysis process (per 1.3 kg input waste).

Entry	Amount	Unit
MONO PE		
Inputs		
Electricity (sorting)	0.07	kWh
Electricity (extra sorting)	0.02	kWh
Electricity (process energy)	0.43	kWh
Heat (process energy)	0.064	kWh
Transportation	0.2	tkm
Outputs		
Natural gas*	0.15	kg
Diesel	0.50	kg
Lignite (or landfill)	0.351	kg
PET/LDPE		
Inputs		
Electricity (sorting)	0.07	kWh
Electricity (extra sorting)	0.02	kWh
Electricity (process energy)	0.43	kWh
Heat (process energy)	0.064	kWh
Transportation	0.2	tkm
Outputs		
Natural gas	0.7	kg
Diesel	0.11	kg
Char: Lignite (or landfill)	0.17	kg

*Natural gas is used as a proxy for pyrolysis gas. The main gases produced were C2 (mainly ethene), C3 (mainly propene), and C4 (mainly butene and butadiene) gases (Sivagami et al. 2021).

For the disposal a fraction of 0.53 and 0.47 are incinerated and landfilled, respectively (Eurostat).The incineration with energy is modelled using Ecoinvent, LHV of plastic mixture (30.79 MJ/kg) and incinerator efficiency to generate heat and electricity (See Appendix).

3.2 Data sources description

The data sources used for each of the datapoints are listed in Table 11. The rest of the data originates from the Ecoinvent and Industry 2.0. See appendix 2 for details on the specific data and processes chosen.

Table 11. Data sources table.

Element	Data source
Film composition	MONO PET Films Europe Consortium
Pyrolysis	(Sivagami et al. 2021; Russ et al. 2020)
Glycolysis	(Schwarz et al. 2021)
EoL statistics	(Antonopoulos et al. 2021)
Metalizing	(Bayus 2015)

3.3 Data quality requirements

Data quality requirements are used to specify the general terms and characteristics of the data needed for the LCA study.
Descriptions of data quality are important to understand the reliability of the study results and to properly interpret the outcome of the study. Table 12 shows the results of the main processes used in the assessments.

Table 12. Pedigree matrix for assessing data quality.

Data category	Reliability	Complete-ness	Temporal correlation	Geographic correlation	Further technological correlation	Result
Film composition	1	1	1	1	1	**1**
Metalizing process	2	2	1	1	1	**1.4**
Pyrolysis	2	2	1	1	1	**1.2**
Glycolysis	2	3	1	1	1	**1.6**
EoL statistics	1	1	1	1	1	**1**

4 Life Cycle Impact Assessment

The impact assessment phase of an LCA is aimed at evaluating the significance of potential environmental impacts using LCI results. In general, this process involves associating inventory data with specific environmental impact categories and category indicators, hereby attempting to understand these impacts.

In this chapter the results are reported for the product system studied. Results are shown for previously defined functional unit (FU) of 1 piece of packaging film. Comparative results are shown relative to the defined benchmark of the PET/LDPE film. Indicators are reported as defined in ”Life cycle impact assessment (LCIA) methodology and types of impact” (section 2.2.6).

4.1 Global warming potential: IPCC Climate change

In order to assess the global warming potential (GWP), in CO_2-eq. of the three packaging films, the IPCC 2013 GWP 100a version 1.03 method is used. Figure 4 illustrates the GWP (in CO_2-eq.) of three packaging types for scenario 1 (SoA with no recycling) per FU. The landfill and incineration emissions and the avoided heat and electricity are shown as the net GWP of waste treatment disposal (EoL burden). Since in scenario 1 no recycling is included the avoided product and thus credit for recycled material is zero. Therefore, material production governs the GWP.

As can be seen from the figure, the cradle-to-grave footprint of MONO PET is 27% lower than PET/LDPE while MONO PE shows a 36% higher burden, compared to PET/LDPE. This is due to two aspects:

1. The 50% recycled fraction of PET; and
2. A lower thickness (44µm in comparison to 76 and 103 µm) which leads to a total film weight of 30.74 g for MONO PET compared to 38.84 g for PET/LDPE and 50.21 g for MONO PE.

The differences in the thickness of the films originate from their stiffness, which means each film should have similar mechanical properties (stiffness) to be comparable.

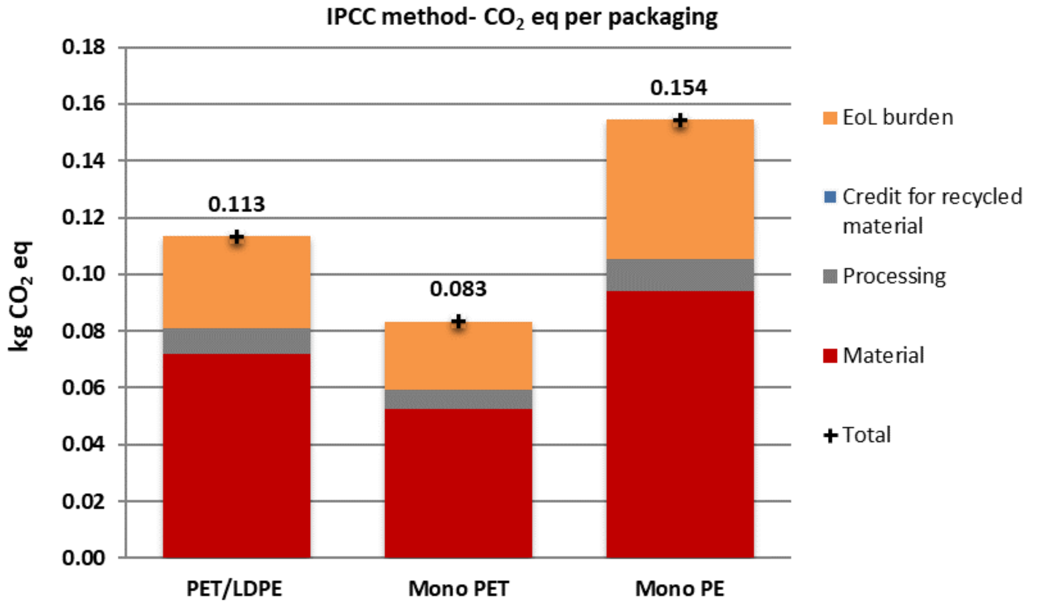

Figure 4. Comparison of the three films and the contribution of different lifecycle stages, by IPCC method (2013 GWP 100a version 1.03). scenario 1: SoA without recycling.

In Figure 5 the results for scenario 2 (future scenario without recycling) are shown, in which the future electricity grid mix is used (with a larger renewable energy part). This results in a smaller GWP burden for the processing of all three films. For PET/LDPE this reduction is 7%, for MONO PET 6% and for MONO PE films 7%.

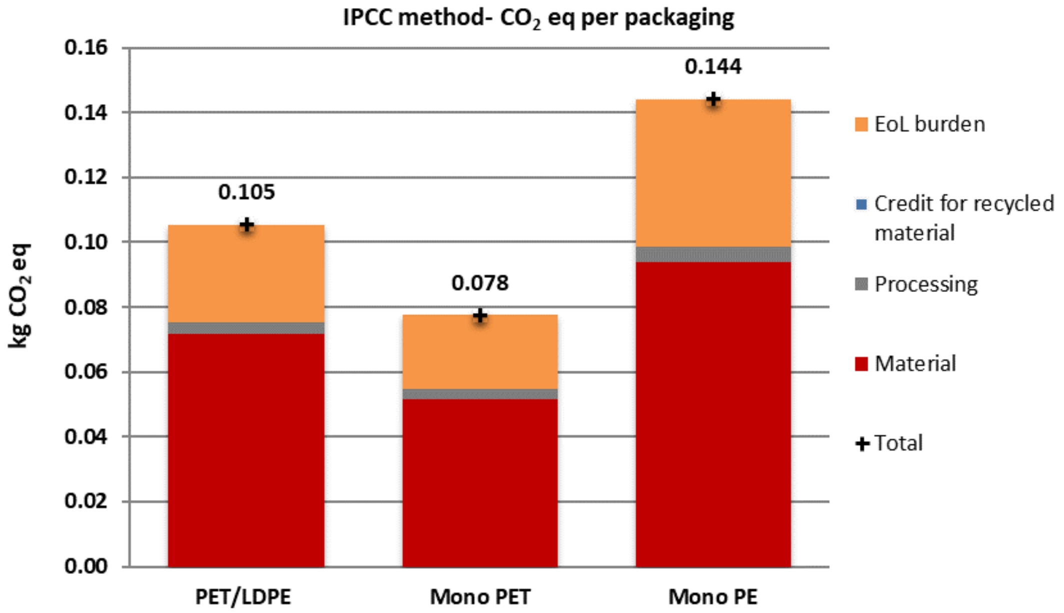

Figure 5. Comparison of the three films and the contribution of different lifecycle stages, by IPCC method (2013 GWP 100a version 1.03). scenario 2: future scenario without recycling.

Figure 6 depicts the results of scenario 3 (future scenario with 69% recycling) whereby 69% recycling occurs for all the films. As can be seen, the chemical recycling of films has reduced the GWP impacts by 24% for PET/LDPE films, 51% for MONO PET films, and 27% for MONO PE compared to scenario 2. The chemical recycling type applied for MONO PET is glycolysis and pyrolysis for the other two packaging alternatives. The avoided CO_2-eq. impact for the PET/LDPE film is 48% lower than MONO PE film, mainly due to higher weight of the MONO PE film. For this study, the fact that 26.8g PET/LDPE is pyrolyzed (entire film is pyrolyzed) in comparison to 34.64g for MONO PE, per packaging, explains the higher burden and avoided product (natural gas and diesel) for the MONO PE use case.

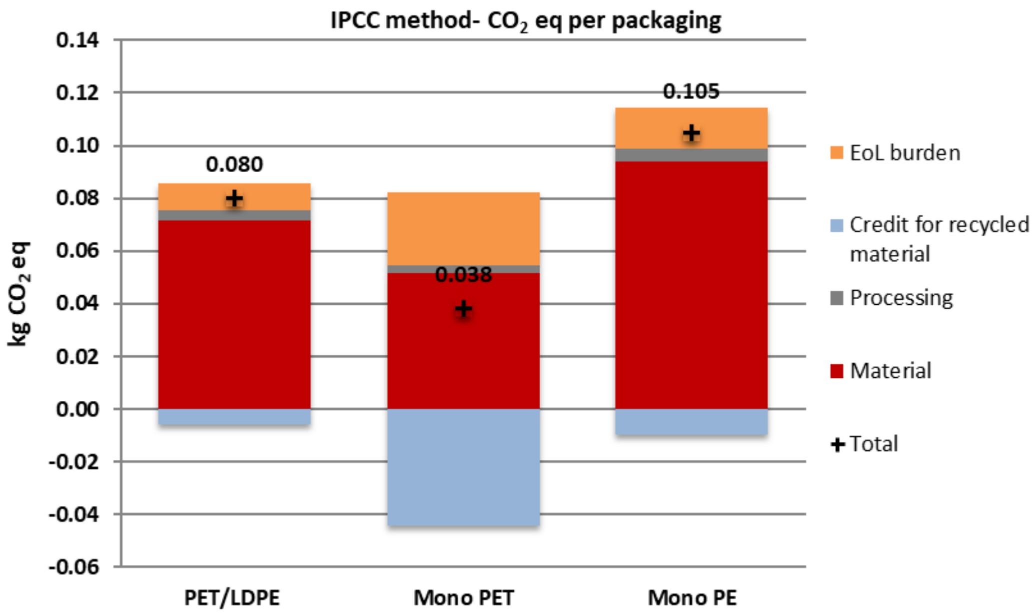

Figure 6. Comparison of the three films and the contribution of different lifecycle stages, by IPCC method (2013 GWP 100a version 1.03). scenario 3: future scenario with 69% recycling.

4.2 Environmental impact: ReCiPe

In order to assess the overall environmental performance of the three packaging films, ReCiPe midpoint (H) method is used. Figure 7 and Figure 8 illustrate the results for the scenario 1 (SoA with no recycling) and 2 (future scenario without recycling), respectively, with the two mono-material films compared with the PET/LDPE benchmark, set at 100%.

It is clear from Figure 7[5] that the production of virgin (BO)PET has a 150% higher potential stratospheric ozone depletion impact than the benchmark PET/LDPE due to the emission of Methane, bromo-, Halon 1001. Bromomethane is an unwanted side product of the xylene oxidation reaction which is used to produce TPA (Plastics Europe).

[5] Note that in a spider diagram all impact categories are considered of equal importance (not normalized). It is therefore best to compare between results of the same impact category.

Similarly, MONO PE has a 250% higher terrestrial ecotoxicity impact than PET/LDPE due to waste treatment (incineration) at EoL whereby a significant amount of vanadium is emitted. Terrestrial acidification and particulate matter formation are also higher for MONO PE due to the emissions of ammonia during ethylene production.

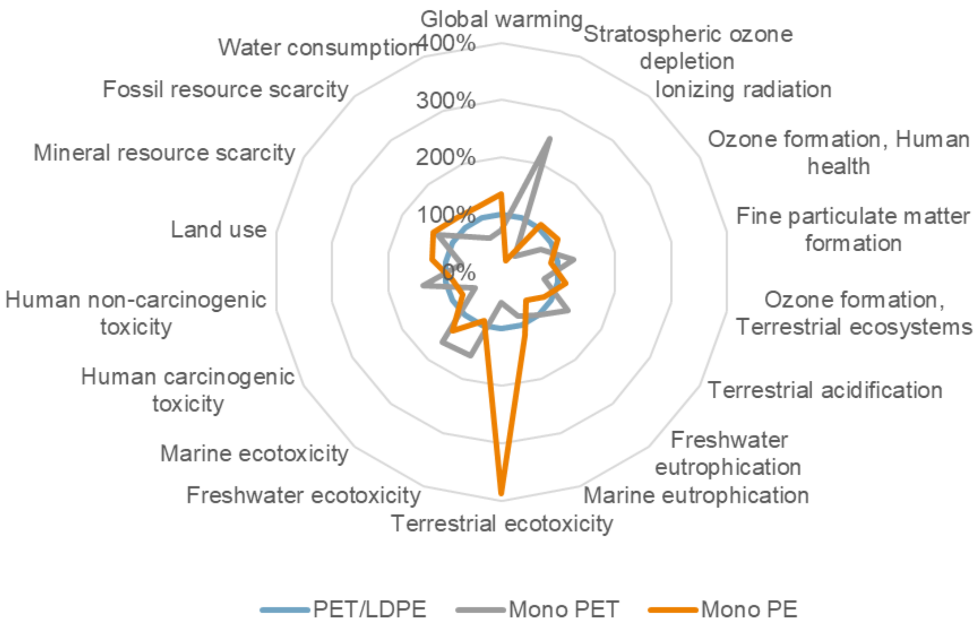

Figure 7. Comparison of the two solutions with reference to the PET/LDPE multilayer film. ReCiPe 2016 Midpoint (H) is used as the impact assessment method. Scenario1: SoA without recycling.

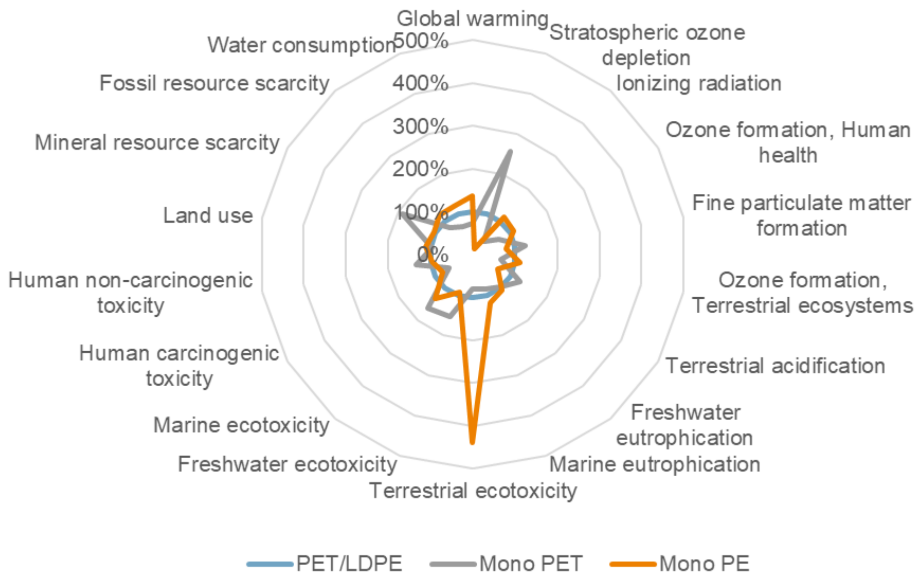

Figure 8. Comparison of the two solutions with reference to the PET/LDPE multilayer film. ReCiPe 2016 Midpoint (H) is used as the impact assessment method. Scenario 2: future without recycling.

Figure 9 shows the results for scenario 3 where recycling is included (69%).

The results dramatically changed for MONO PET films specially for mineral resource scarcity. This is a result of two contributions. Firstly, the production of PET involves the use of TPA.

Typically an antimony or titanium compound is used as a catalyst, a phosphite is added as a stabilizer and a bluing agent such as cobalt salt is added to mask any yellowing (Macdonald 2002). Secondly, during the glycolysis of PET different catalysts are used such as zinc acetate, lead-, cobalt-, or manganese acetate, and titanium alkoxides. This is due to the fact that glycolysis without a catalyst is a sluggish reaction with an activation energy of 32 kcal/mol, while the catalysed process requires only 19 kcal/ mol (Troev et al. 2003). In this work the worst-case scenario is used (Cobalt ion) which has a high burden in terms of mineral resource scarcity (3.79 kg Cu eq. vs. 0.676 kg Cu eq. per kg, for titanium dioxide). Thus, when a higher recycling rate takes place, the Cobalt ions are more consumed. It is recommended to switch to other salts if (technically) possible at the moment. In practice, the recovery of small amounts of metal catalyst is cumbersome and does not take place.

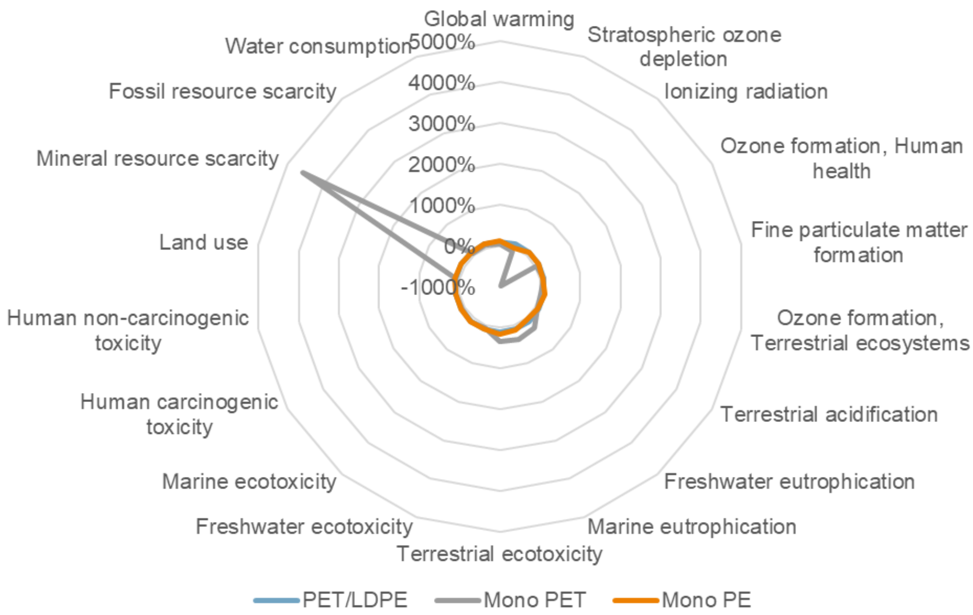

Figure 9. Comparison of the two solutions with reference to the PET/LDPE multilayer film. ReCiPe 2016 Midpoint (H) is used as the impact assessment method. Scenario 3.

5 Interpretation & Sensitivity Analysis

The sensitivity analysis is carried out to investigate the GWP impact of full recyclability (100% recycling rate) of the films, excluding disposal during the collection stage. The difference between sensitivity analysis 1: state-of-the-art (SoA) and sensitivity analysis 2: future, corresponds to the electricity grid mix in the recycling and processing of the films as well as the technology development level (efficiency) (see page 11).

Figure 10 and Figure 11 show the result of GWP for the sensitivity analysis 1 and 2, respectively. For the current situation (SoA), sensitivity analysis 1, it is evident that for fully recyclable films (100% recycling rate), MONO PET performs 37% better than PET/LDPE and 49% better MONO PE. Using more renewable energy, is very beneficial during recycling stage, especially during pyrolysis whereby the EoL burden is almost negligible (Figure 11).

In the SoA situation where all films are chemically recycled (sensitivity 1), the GWP has decreased substantially in comparison to the actual situation happening in Europe (scenario 1). This is 36% for MONO PE, 40% for MONO PET and 30% PET/LDPE films, respectively, when the GWP of each film from scenario 1 and sensitivity 1 is compared (Table 9). This reduction is even higher for the future scenario (sensitivity 2) where renewable electricity is used for the recycling: 41% for MONO PE, 75% for MONO PET and 36% for PET/LDPE films, respectively.

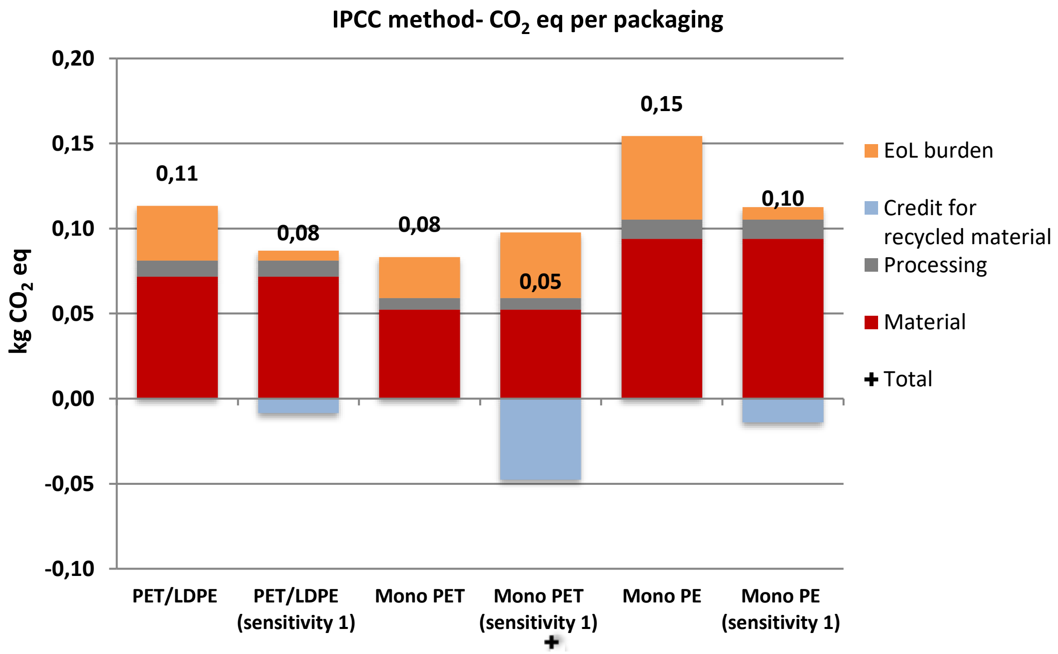

Figure 10. Comparison of the three films and the contribution of different lifecycle stages, by IPCC method (2013 GWP 100a version 1.03). Sensitivity 1; 100% recycling SoA.

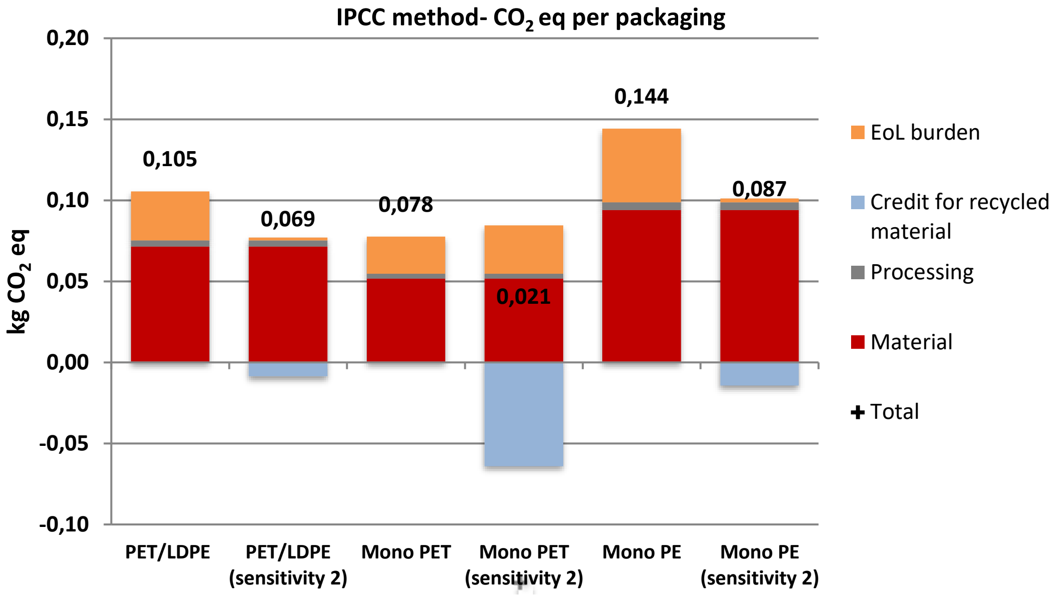

Figure 11. Comparison of the three films and the contribution of different lifecycle stages, by IPCC method (2013 GWP 100a version 1.03). Sensitivity 2: 100% recycling future.

As discussed in section 4.2. the effect of the catalyst on the mineral resource scarcity of PET glycolysis is important. Figure 12 depicts the result of sensitivity analysis 1 by using ZnO_2, TiO_2 and CoO_2 as the catalyst. These metal-oxides are not used as is during the glycolysis process, but the impact of different forms of metallic compound would be similar to these metal-oxides as their content of metals are equivalent. As can be seen, while using CoO_2 has a large impact on the mineral resource scarcity the use of ZnO_2 can decrease the impact of catalyst significantly. Additionally, the use of Cobalt as a catalyst for food contact material is no longer used as a catalyst in Europe and is going to be further phased out globally in the near future. Thus, the effect of Cobalt can be neglected for the production and recycling of the films.

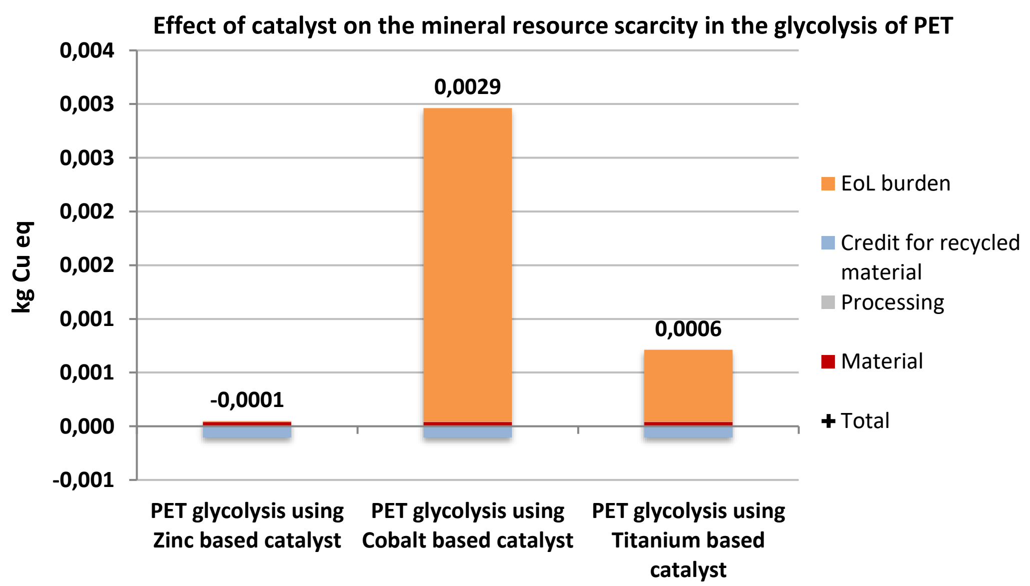

Figure 12. Catalyst effect on mineral resource scarcity (kg Cu eq.) of PET glycolysis, per FU & cradle to grave. For sensitivity analysis 1, metal catalysts zinc, cobalt & titanium.

6 Conclusions and recommendations

The LCA assessed the environmental impact of the two proposed mono material film alternative solutions (MONO PET and MONO PE) compared with the reference case, a laminate made from PET and LDPE. The two alternative solutions are made from mainly PE and PET which improves their recyclability.

From this comparative cradle-to-grave LCA study it is clear that the mono-material design for packaging films made from MONO PET, has a lower overall global warming potential (GWP in CO_2-eq.). This is the case in all three scenarios (1: state-of-the art, 2: future without recycling, 3: future with 69% recycling) and is due to the lower overall weight of the film (30.74g for MONO PET, 38.84g for PET/LDPE, and 50.21g for MONO PE), and due to it being better recyclable.

This benefit can be increased if the collection and sorting infrastructure is improved. Currently packaging films smaller than A4, although collected, are often not sorted to a DKR-fraction6 (quality specification) for recycling in Europe. This leads to limitations for the recyclability of the newly designed films.

For the specific application of dry food (muesli) packaging the MONO PE films do not show promising results due to the importance of stiffness of the pouch and thus a higher required thickness. This will hinder reaching full circularity, as a result of currently low sorting and recycling rates for multilayer packaging films.

Based on the LCA analysis of the three packaging films, it is concluded that:

- In all scenarios, MONO PET has a lower environmental impact than PET/LDPE and MONO PE. Moreover, the environmental impact of PET/LDPE (the incumbent design) is lower than MONO PE which shows the MONO material option is not always better in terms of environmental performance. This is due to the thickness and thus weight of the films; MONO PE is the thickest films followed by PET/LDPE.

- The benefits of design for recycling, for mono-material films (MONO PET and MONO PE) can be obtained when at least the separately collected films (69%) are sorted and recycled. It is important to use mixed streams of PET and polyolefins to reduce the oxygen content of the stream to facilitate the pyrolysis process.
- The thickness of the films and their functionality which is required for the intended application, in this study for muesli packaging, has a critical role in the environmental performance. The use of thin film in addition to recycled fraction (50%) for PET can improve the results significantly.
- When reaching a hypothetical 100% recycling rate for packaging films, 36%, 40% and 30% reduction in global warming potential (GWP in CO_2-eq.) is observed for MONO PE, MONO PET and PET/LDPE, respectively.

---

[6] Deutsche Gesellschaft für Kunststoff Recycling

This reduction is even higher for the future scenario where renewable electricity is used for the recycling (mechanical, pyrolysis and glycolysis); 41% for MONO PE, 75% for MONO PET and 36% for PET/LDPE films, respectively.

6.1.1 Limitations

The impact assessment of pyrolysis involves many assumptions. In reality, the results highly depend on the type, scale and pyrolysis condition which leads to different products. The same applies to glycolysis. These technologies have a low technological readiness level (low TRL), requiring further development and therefore, the generated results can only be indicative of the technologies as they are applied in this study. It is recommended to treat the outcome of the study with care. Similarly, the functionality of the films depends on the application of the films and by changing the thickness, where for instance modulus is less relevant, different results may be obtained.

7 References

Anon. File:Municipal waste landfilled, incinerated, recycled and composted, EU-27, 1995-2019.png - Statistics Explained. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Municipal_waste_landfilled,_incinerated,_recycled_and_composted,_EU-27,_1995-2019.png#file.

Antonopoulos, I., G. Faraca, and D. Tonini. 2021. Recycling of post-consumer plastic packaging waste in the EU: Recovery rates, material flows, and barriers. *Waste Management* 126: 694–705. https://www.sciencedirect.com/science/article/pii/S0956053X21001999.

Billiet, S. and S.R. Trenor. 2020. 100th Anniversary of Macromolecular Science Viewpoint: Needs for Plastics Packaging Circularity. *ACS Macro Letters* 9(9): 1376–1390. https://doi.org/10.1021/acsmacrolett.0c00437.

Catalán, E., D. Komilis, and A. Sánchez. 2019. Environmental impact of cellulase production from coffee husks by solid-state fermentation: A life-cycle assessment. *Journal of Cleaner Production* 233: 954–962. https://www.sciencedirect.com/science/article/pii/S095965261932058X.

Chen, Q., Z. Wang, S. Zhang, Y. Cao, and J. Chen. 2020. Structure Evolution and Deformation Behavior of Polyethylene Film during Biaxial Stretching. *ACS Omega* 5(1): 655–666. https://doi.org/10.1021/acsomega.9b03250.

Dow. 2018. Dow TF BOPE Sustainable Packaging Solutions and ENGAGE PV POE win 2018 R D 100 Awards. https://corporate.dow.com/en-us/news/press-releases/dow-tf-bope-sustainable-packaging-solutions-and-engage-pv-poe-win-2018-r-d-100-awards.html.

Environmental management - Life cycle assessment - Principles and framework (ISO 14040:2006 + Amd 1:2020)

Environmental management - Life cycle assessment - Requirements and guidelines (ISO 14044:2006 + Amd 1:2017 + Amd 2:2020)

European Commission, Critical materials for strategic technologies and sectors in the EU - a foresight study, 2020.

Groh, K.J., T. Backhaus, B. Carney-Almroth, B. Geueke, P.A. Inostroza, A. Lennquist, H.A. Leslie, et al. 2019. Overview of known plastic packaging-associated chemicals and their hazards. *Science of The Total Environment* 651: 3253–3268. https://www.sciencedirect.com/science/article/pii/S0048969718338828.

Huijbregts, M.A.J., Z.J.N. Steinmann, P.M.F. Elshout, G. Stam, F. Verones, M. Vieira, M. Zijp, A. Hollander, and R. van Zelm. 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *The International Journal of Life Cycle Assessment* 22(2): 138–147. https://doi.org/10.1007/s11367-016-1246-y.

ISO. 2018. Environmental management - Life cycle assessment - Requirements and guidelines (ISO 14044:2006/Amd 1:2017). CEN-CENELEC.

Kusenberg, M., A. Zayoud, M. Roosen, H.D. Thi, M.S. Abbas-Abadi, A. Eschenbacher, U. Kresovic, S. De Meester, and K.M. Van Geem. 2022. A comprehensive experimental investigation of plastic waste pyrolysis oil quality and its dependence on the plastic waste composition. *Fuel Processing Technology* 227: 107090. https://www.sciencedirect.com/science/article/pii/S0378382021003714.

Macdonald, W. 2002. New advances in poly(ethylene terephthalate) polymerization and degradation. *Polymer International* 51: 923–930.

Maga, D., M. Hiebel, and V. Aryan. 2019. A Comparative Life Cycle Assessment of Meat Trays Made of Various Packaging Materials. *Sustainability* 11: 5324.

Ren, M., Y. Tang, D. Gao, Y. Ren, X. Yao, H. Shi, T. Zhang, and C. Wu. 2020. Recrystallization of biaxially oriented polyethylene film from partially melted state within crystallite networks. *Polymer* 191: 122291. https://www.sciencedirect.com/science/article/pii/S0032386120301300.

Rodrigues, M., S. Quevedo, J. Souza, and J. Farias. 2020. Waste Recycling in Biaxially Oriented Polypropylene -BOPP 10: 11–15.

Russ, M., M. Gonzalez, and M. Horlacher. 2020. *Life cycle assessment (LCA) for ChemCycling™*. https://www.basf.com/global/en/who-we-are/sustainability/we-drive-sustainable-solutions/circular-economy/mass-balance-approach/chemcycling/lca-for-chemcycling.html.

SABIC. 2021. SABIC - SABIC launches innovative TF-BOPE FILM for frozen food packaging. https://www.sabic.com/en/news/24224-sabic-launches-innovative-tf-bope-film-for-frozen-food-packaging.

Schwarz, A.E., T.N. Ligthart, D. Godoi Bizarro, P. De Wild, B. Vreugdenhil, and T. van Harmelen. 2021. Plastic recycling in a circular economy; determining environmental performance through an LCA matrix model approach. *Waste Management* 121: 331–342. https://www.sciencedirect.com/science/article/pii/S0956053X20307091.

Siracusa, V., M. Dalla Rosa, S. Romani, P. Rocculi, and U. Tylewicz. 2011a. Life Cycle Assessment of multilayer polymer film used on food packaging field. *Procedia Food Science* 1: 235–239.

Siracusa, V., C. Ingrao, A. Lo Giudice, C. Mbohwa, and M. Dalla Rosa. 2014. Environmental assessment of a multilayer polymer bag for food packaging and preservation: An LCA approach. *Food Research International* 62: 151–161. https://www.sciencedirect.com/science/article/pii/S0963996914001094.

Siracusa, V., M.D. Rosa, S. Romani, P. Rocculi, and U. Tylewicz. 2011b. Life Cycle Assessment of multilayer polymer film used on food packaging field. *Procedia Food Science* 1: 235–239. https://www.sciencedirect.com/science/article/pii/S2211601X11000381.

Sivagami, K., G. Divyapriya, R. Selvaraj, P. Madhiyazhagan, N. Sriram, and I. Nambi. 2021. Catalytic pyrolysis of polyolefin and multilayer packaging based waste plastics: A pilot scale study. *Process Safety and Environmental Protection* 149: 497–506. https://www.sciencedirect.com/science/article/pii/S0957582020318346.

Troev, K., G. Grancharov, R. Tsevi, and I. Gitsov. 2003. A novel catalyst for the glycolysis of poly(ethylene terephthalate). *Journal of Applied Polymer Science* 90(4): 1148–1152. https://doi.org/10.1002/app.12711.

Veksha, A., K. Yin, J.G.S. Moo, W.-D. Oh, A. Ahamed, W.Q. Chen, P. Weerachanchai, A. Giannis, and G. Lisak. 2020. Processing of flexible plastic packaging waste into pyrolysis oil and multi-walled carbon nanotubes for electrocatalytic oxygen reduction. *Journal of Hazardous Materials* 387: 121256. https://www.sciencedirect.com/science/article/pii/S0304389419312105.

8 Signature

Name and address of the principal:
BOPET Films Europe
Avenue Louise, 209 A
B-1050, Brussels
Belgium

Names of the authors:
Dr. Golkaram, M., Heemskerk, L.P.

Date upon which, or period in which the research took place:
October 2021 - August 2022

Name and signature reviewer:

ValidSigned by Tom Ligthart
on 2022-09-21 15:17:41

Tom Ligthart

Signature:

ValidSigned by lisanne Heemskerk
on 2022-09-21 14:17:26

Lisanne Heemskerk
Project manager

Release:

ValidSigned by Gerard van der Laan
on 2022-09-21 14:30:26

Gerard van der Laan
Research Manager

Appendix 1. Material flow

Table A 1. The material flow diagram for the 3 scenarios and 2 sensitivity analysis. All the values are in grams.

Scenario	Material production		Product manufacturing	Functional unit (g)	EoL (g)				Avoided products (g)					
		Total mass (g)			Incineratior	Landfill	Pyrolysis	Glycolysis	Lignite	Diesel	NG	TPA	PET	EG
1	PET/LDPE	39.79	Extrusion + Lamination + vacuum deposition	38.84	20.58	18.25								
	BOPET	30.74	Biaxial orientation + vacuum deposition	30.74	16.29	14.45								
	BOPE	51.44	Co-extrusion + Biaxial orientation	50.21	26.61	23.60								
2	PET/LDPE	39.79	Extrusion + Lamination + vacuum deposition	38.84	34.95	3.88								
	BOPET	30.74	Biaxial orientation + vacuum deposition	30.74	27.66	3.07								
	BOPE	51.44	Co-extrusion + Biaxial orientation	50.21	45.18	5.02								
3	PET/LDPE	39.79	Extrusion + Lamination + vacuum deposition	38.84	10.87	1.17	26.80		9.647	7.146	9.111			
	BOPET	30.74	Biaxial orientation + vacuum deposition	30.74	8.61	0.92		21.21					18.76	6.057
	BOPE	51.44	Co-extrusion + Biaxial orientation	50.21	14.06	1.51	34.64		9.353	17.41	5.196			
Sensitivity 1	PET/LDPE	39.79	Extrusion + Lamination + vacuum deposition	38.84	0.00	0.00	38.84			19.52	13.2			
	BOPET	30.74	Biaxial orientation + vacuum deposition	30.74	0.00	0.00		30.74				27.97		
	BOPE	51.44	Co-extrusion + Biaxial orientation	50.21	0.00	0.00	50.21			25.24	7.531			
Sensitivity 2	PET/LDPE	39.79	Extrusion + Lamination + vacuum deposition	38.84	0.00	0.00	38.84		13.98	10.36	13.2			
	BOPET	30.74	Biaxial orientation + vacuum deposition	30.74	0.00	0.00		30.74					27.18	8.778
	BOPE	51.44	Co-extrusion + Biaxial orientation	50.21	0.00	0.00	50.21		13.56	25.24	7.531			

Appendix 2. 'Database references'

	Materials				
Product type	**Process used**	**Primary data**	**Secondary data**	**Source**	**Description / Data source:**
LDPE	Polyethylene, LDPE, granulate, at plant/RER	✓		Industry 2.0	Thickness of the films were provided by BOPET. The detail of the calculations on the mass flow is in the Annex 2.
LLDPE	Polyethylene, LLDPE, granulate, at plant/RER	✓		Industry 2.0	Thickness of the films were provided by BOPET. The detail of the calculations on the mass flow is in the Annex 2.
PET	PET, bottle grade, at plant/RER	✓		Industry 2.0	Thickness of the films were provided by BOPET. The detail of the calculations on the mass flow is in the Annex 2.
Glue and tie layer	Ethylene vinyl acetate copolymer {RER}| production | APOS, U	✓		Ecoinvent 3.8	Thickness of the films were provided by BOPET. The detail of the calculations on the mass flow is in the Annex 2.
Al	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for | APOS, U	✓		Ecoinvent 3.8	Thickness of the films were provided by BOPET. The detail of the calculations on the mass flow is in the Annex 2.
rPET (SoA)	Recycled postconsumer PET pellet/RNA	✓		USLCI	Thickness of the films were provided by BOPET. The detail of the calculations on the mass flow is in the Annex 2.
rPET(future)	Polyethylene terephthalate, granulate, amorphous {RER}| production | APOS, U	✓		Ecoinvent 3.8	Thickness of the films were provided by BOPET. The detail of the calculations on the mass flow is in the Annex 2. Ecoinvent is used as the Industry 2.0 does not contain unit process. In the Ecoinvent process, the monomer TPA is replaced by the recycled monomer from glycolysis and forms recycled PET via polymerization based on Ecoinvent LCI.

				Processing	
Product type	**Process used**	**Primary data**	**Secondary data**		**Description / Data source:**
Extrusion	Extrusion, plastic film {RER}| extrusion, plastic film | APOS, U	✓		Ecoinvent 3.8	Thickness of the films were provided by BOPET. The detail of the calculations on the mass flow is in the Annex 2.
Co-extrusion**	Extrusion, co-extrusion {GLO}| market for | APOS, U	✓		Ecoinvent 3.8	Thickness of the films were provided by BOPET. The detail of the calculations on the mass flow is in the Annex 2.

				Metalizing
Product type	**Process used**	**Primary data**	**Secondary data**	**Description / Data source:**
Electricity	Electricity 2021 (EuroStat 2022), low voltage {EU}| market for | APOS, U		✓	Ecoinvent 3.8
	Electricity 2050 (IEA 2021), low voltage {EU}| market for | APOS, U		✓	Ecoinvent 3.8

Boron Nitride	Boron carbide {GLO}| market for | APOS, U		✓	Boron carbide was chosen as a proxy for Boron Nitride	Ecoinvent 3.8
Titanium diboride	Titanium dioxide {RER}| market for | APOS, U		✓	Titanium dioxide is chosen as a proxy forTitanium diboride	Ecoinvent 3.8
Lamination					
Product type	**Process used**	**Primary data**	**Secondary data**		**Description / Data source:**
Electricity	Electricity 2021 (EuroStat 2022), low voltage {EU}| market for | APOS, U	✓		Ecoinvent 3.8	0.533 kwh per kg electricity is added to the Ecoinvent Extrusion process as extra energy required. This amount is **confidential** and is based on TNO database in other projects.
	Electricity 2050 (IEA 2021), low voltage {EU}| market for | APOS, U	✓		Ecoinvent 3.8	
Extrusion	Extrusion, plastic film {RER}| extrusion, plastic film | APOS, U		✓	Ecoinvent 3.8	

Collection per kg waste							
Product type	**Process used**	**Primary data**	**Secondary data**	**Type**	**Amount (tkm)**		**Description / Data source**
Transportation	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5		✓	Kerbside	11.9	Ecoinvent 3.8	https://publications.jrc.ec.europa.eu/repository/handle/JRC122455
Transportation	Transport, freight, lorry 3.5-7.5 metric ton, euro5 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO5		✓	Kerbside	17.1	Ecoinvent 3.8	https://publications.jrc.ec.europa.eu/repository/handle/JRC122455
Transportation	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5		✓	Street collection	13.9	Ecoinvent 3.8	https://publications.jrc.ec.europa.eu/repository/handle/JRC122455
Transportation	Transport, freight, lorry 3.5-7.5 metric ton, euro5 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO5		✓	Drop-off areas	0.3	Ecoinvent 3.8	https://publications.jrc.ec.europa.eu/repository/handle/JRC122455
Sorting per kg waste							
Product type	**Process used**	**Primary data**	**Secondary data**		**Amount**		**Description / Data source**
Electricity	Electricity, low voltage {RER}| market group for		✓		0,016 kwh	Ecoinvent 3.8	LCI database
Heat	Diesel, combusted in industrial boiler/US		✓		0,0018 l	USLCI	LCI database
Transportation	Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | APOS, U		✓		0,03 tkm	Ecoinvent 3.8	LCI database
Heat	Liquefied petroleum gas, combusted in industrial boiler/US		✓		0,0025 l	USLCI	LCI database
Heat	Natural gas, combusted in industrial boiler/US		✓		0,0000022 m3	USLCI	LCI database

Glycolysis					
Product type	**Process used**	**Primary data**	**Secondary data**	**Description / Data source:**	
Ethylene glycol	Ethylene glycol {GLO}| market for | APOS, U		✓	Ecoinvent 3.8	
Cobalt (acetate)	cobalt acetate {GLO}| cobalt production | APOS, U		✓	Ecoinvent 3.8	
Soap	Soap {GLO}| market for | APOS, U		✓	Ecoinvent 3.8	
Water	water, completely softened {RER}| market for water, completely softened | APOS, U		✓	Ecoinvent 3.8	
Electricity	Electricity, medium voltage {RER}| market group for | APOS, U		✓	Ecoinvent 3.8	
Transportation	Transport, freight, lorry >32 metric ton, EURO6 {RER}| transport, freight, lorry >32 metric ton, EURO6 | APOS, U		✓	Ecoinvent 3.8	
Wastewater	Wastewater, average {Europe without Switzerland}| treatment of wastewater, average, capacity 1E9l/year | APOS, U		✓	Ecoinvent 3.8	
Waste plastic	Waste polyethylene terephtalate {RER}| treatment of, municipal incineration | APOS, U		✓	Ecoinvent 3.8	
TPA (current scenario)	Purified terephthalic acid {RER}| production | APOS, U		✓	Ecoinvent 3.8	
Polymerization of TPA	Polyethylene terephthalate, granulate, amorphous {RER}| production | APOS, U		✓	Ecoinvent 3.8	
PET (future scenario)	Polyethylene terephthalate, granulate, bottle grade, at plant/RER		✓	Ecoinvent 3.8	Polyethylene terephthalate, granulate, amorphous {RER}| production | APOS, U is the process for polymerization whereby PET and EG are avoided at the end of the production.
EG (future scenario)	Ethylene glycol {GLO}| market for | APOS, U		✓	Ecoinvent 3.8	Polyethylene terephthalate, granulate, amorphous {RER}| production | APOS, U is the process for polymerization whereby PET and EG are avoided at the end of the production.

Pyrolysis avoided				
Product type	**Process used**	**Primary data**	**Secondary data**	**Description / Data source:**
Diesel	Diesel, low-sulfur {RER}| market group for | APOS, U		✓	Ecoinvent 3.8
Natural gas	Natural gas, extracted/kg/RNA		✓	USLCI
Lignite (char)	Lignite {RER}| market for | APOS, U		✓	Ecoinvent 3.8

Pyrolysis Burden					
Product type	**Process used**	**Primary data**	**Secondary data**	**Description / Data source**	
Electricity (sorting)	Electricity 2021 (EuroStat 2022), low voltage {EU}| market for | APOS, U		✓	Ecoinvent 3.8	Electricity 2050 (IEA 2021), low voltage {EU}| market for | APOS, U is used for the future scenarios
Electricity (extra sorting)	Electricity 2021 (EuroStat 2022), low voltage {EU}| market for | APOS, U		✓	Ecoinvent 3.8	Electricity 2050 (IEA 2021), low voltage {EU}| market for | APOS, U is used for the future scenarios
Electricity (process energy)	Electricity 2021 (EuroStat 2022), low voltage {EU}| market for | APOS, U		✓	Ecoinvent 3.8	Electricity 2050 (IEA 2021), low voltage {EU}| market for | APOS, U is used for the future scenarios
Heat (process energy)	Electricity 2021 (EuroStat 2022), low voltage {EU}| market for | APOS, U		✓	Ecoinvent 3.8	Electricity 2050 (IEA 2021), low voltage {EU}| market for | APOS, U is used for the future scenarios
Transportation	Transport, freight, lorry >32 metric ton, EURO6 {RER}| transport, freight, lorry >32 metric ton, EURO6 | APOS, U		✓	Ecoinvent 3.8	Electricity 2050 (IEA 2021), low voltage {EU}| market for | APOS, U is used for the future scenarios
Waste	Inert waste, for final disposal {CH}| treatment of inert waste, inert material landfill | APOS, U		✓	Ecoinvent 3.8	Electricity 2050 (IEA 2021), low voltage {EU}| market for | APOS, U is used for the future scenarios

Disposal (landfill and incineration) of BOPE per kg waste					
Product type	**Process used**	**Primary data**	**Secondary data**	**Amount**	**Description / Data source**
MONO PE					
Emissions of incineration	Waste polyethylene {RER}| treatment of waste polyethylene, municipal incineration		✓	1 kg	Ecoinvent 3.8
Electricity recovery	Electricity 2021 (EuroStat 2022), low voltage {EU}| market for | APOS, U		✓	-6.88 MJ	Ecoinvent 3.8
Heat recovery	Heat, central or small-scale, natural gas {Europe without Switzerland}| market for heat, central or small-scale, natural gas		✓	-2.76 MJ	Ecoinvent 3.8
Heat recovery	Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace low-NOx >100kW		✓	-5.82 MJ	Ecoinvent 3.8
Transportation	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U		✓	0.0132 tkm	Ecoinvent 3.8 https://publications.jrc.ec.europa.eu/repository/handle/JRC122455
PET/LDPE					
Emissions of incineration	Waste plastic, mixture {RER}| treatment of waste plastic, mixture, municipal incineration		✓	1 kg	Ecoinvent 3.8
Electricity recovery	Electricity 2021 (EuroStat 2022), low voltage {EU}| market for | APOS, U		✓	-4.99 MJ	Ecoinvent 3.8
Heat recovery	Heat, central or small-scale, natural gas {Europe without Switzerland}| market for heat, central or small-scale, natural gas		✓	-2.0 MJ	Ecoinvent 3.8
Heat recovery	Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace low-NOx >100kW		✓	-4.22 MJ	Ecoinvent 3.8

Transportation	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U		✓	0.0132 tkm	Ecoinvent 3.8 https://publications.jrc.ec.europa.eu/repository/handle/JRC122455
MONO PET					
Emissions of incineration	Waste polyethylene {RER}| treatment of waste polyethylene, municipal incineration		✓	1 kg	Ecoinvent 3.8
Electricity recovery	Electricity 2021 (EuroStat 2022), low voltage {EU}| market for | APOS, U		✓	-3.72 MJ	Ecoinvent 3.8 Elektrisch rendement AVI 2018 (was 0.169 en eerder 0.2092). berekening gewogen gemiddelde AVI's NL. Rendement op basis van LHV input. bron: Werkgroep Afvalregistratie. (2020). Afvalverwerking in Nederland, gegevens 2018. Klimaat en Energieverkenning 2019. ; M.B.J. (Matthijs) Otten, G.C. (Geert) Bergsma, 2010, Beter één AVI met een hoog rendement dan één dichtbij. Hoeveel transport van afval is nuttig voor een hoger energierendement. CE oktober 2010
Heat recovery	Heat, central or small-scale, natural gas {Europe without Switzerland}| market for heat, central or small-scale, natural gas		✓	-3.14 MJ	Ecoinvent 3.8 Elektrisch rendement AVI 2018 (was 0.169 en eerder 0.2092). berekening gewogen gemiddelde AVI's NL. Rendement op basis van LHV input. bron: Werkgroep Afvalregistratie. (2020). Afvalverwerking in Nederland, gegevens 2018. Klimaat en Energieverkenning 2019. ; M.B.J. (Matthijs) Otten, G.C. (Geert) Bergsma, 2010, Beter één AVI met een hoog rendement dan één dichtbij. Hoeveel transport van afval is nuttig voor een hoger energierendement. CE oktober 2010ent/
Heat recovery	Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace low-NOx >100kW		✓	-1.49 MJ	Ecoinvent 3.8 Elektrisch rendement AVI 2018 (was 0.169 en eerder 0.2092). berekening gewogen gemiddelde AVI's NL. Rendement op basis van LHV input. bron: Werkgroep Afvalregistratie. (2020). Afvalverwerking in Nederland, gegevens 2018. Klimaat en Energieverkenning 2019. ; M.B.J. (Matthijs) Otten, G.C. (Geert) Bergsma, 2010, Beter één AVI met een hoog rendement dan één dichtbij. Hoeveel transport van afval is nuttig voor een hoger energierendement. CE oktober 2010
Transportation	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U		✓	0.0132 tkm	Ecoinvent 3.8 https://publications.jrc.ec.europa.eu/repository/handle/JRC122455
Product type	**Process used**	**Primary data**	**Secondary data**	**Amount**	**Description / Data source**
Landfill	Waste plastic, mixture {GLO}| treatment of waste plastic, mixture, unsanitary landfill, moist infiltration class (300mm) | APOS, U		✓	1 kg	Ecoinvent 3.8
Additional transportation	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | APOS, U		✓	0.069 tkm	Ecoinvent 3.8

		Incineration with energy recovery	
Parameter	**Value**	**Reference**	**Description / Data source**

AVI_eff_Hwkk	0.022	https://www.pbl.nl/sites/default/files/downloads/pbl-2019-klimaat-en-energieverkenning-2019-3508.pdf https://www.afvalcirculair.nl/onderwerpen/linkportaal/publicaties/downloads/downloads-0/afvalverwerking-nederland-gegevens-2018/ https://ce.nl/publicaties/beter-een-avi-met-een-hoog-rendement-dan-een-dichtbijhoeveel-transport-van-afval-is-nuttig-voor-een-hoger-energierendement/	Efficiency of heat production Warmtekracht-koppelingsinstallaties
AVI_eff_Hind	0.115	https://www.pbl.nl/sites/default/files/downloads/pbl-2019-klimaat-en-energieverkenning-2019-3508.pdf https://www.afvalcirculair.nl/onderwerpen/linkportaal/publicaties/downloads/downloads-0/afvalverwerking-nederland-gegevens-2018/ https://ce.nl/publicaties/beter-een-avi-met-een-hoog-rendement-dan-een-dichtbijhoeveel-transport-van-afval-is-nuttig-voor-een-hoger-energierendement/	Efficiency of heat production for industry
AVI_eff_Hhh	0.065	https://www.pbl.nl/sites/default/files/downloads/pbl-2019-klimaat-en-energieverkenning-2019-3508.pdf https://www.afvalcirculair.nl/onderwerpen/linkportaal/publicaties/downloads/downloads-0/afvalverwerking-nederland-gegevens-2018/ https://ce.nl/publicaties/beter-een-avi-met-een-hoog-rendement-dan-een-dichtbijhoeveel-transport-van-afval-is-nuttig-voor-een-hoger-energierendement/	Efficiency of heat production for households
AVI_eff_E	0.162	https://www.pbl.nl/sites/default/files/downloads/pbl-2019-klimaat-en-energieverkenning-2019-3508.pdf https://www.afvalcirculair.nl/onderwerpen/linkportaal/publicaties/downloads/downloads-0/afvalverwerking-nederland-gegevens-2018/ https://ce.nl/publicaties/beter-een-avi-met-een-hoog-rendement-dan-een-dichtbijhoeveel-transport-van-afval-is-nuttig-voor-een-hoger-energierendement/	Efficiency of electricity production
		Incineration with energy recovery	
Process	**Value**		**Description / Data source**
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace low-NOx >100kW | Cut-off, U	LHV_plastic_mix* (AVI_eff_Hind+ AVI_eff_Hwkk) = 4.22 MJ		Heat generation for industry use
Heat, central or small-scale, natural gas {Europe without Switzerland}| market for heat, central or small-scale, natural gas | Cut-off, U	LHV_plastic_mix*AVI_eff_Hhh =2 MJ		Heat generation for house hold
Electricity, high voltage {RER}| market group for | Cut-off, U	LHV_plastic_mix*AVI_eff_E =4.99 MJ		Electricity generation

Appendix 3. Results

Table A.2. ReCiPe midpoint (H) results for the three films for scenario 1.

Impact category	Unit	PET/LDPE	MONO PET	MONO PE
Global warming	kg CO2 eq	0.114408763	0.08409997	0.155824531
Stratospheric ozone depletion	kg CFC11 eq	1.21925E-07	3.01745E-07	2.39824E-08
Ionizing radiation	kBq Co-60 eq	0.001627598	0.000569021	0.001738542
Ozone formation, Human health	kg NOx eq	0.000167941	0.000133863	0.000188411
Fine particulate matter formation	kg PM2.5 eq	5.01868E-05	6.35786E-05	4.40877E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.000186484	0.000139468	0.000212108
Terrestrial acidification	kg SO2 eq	0.000154459	0.000206874	0.000133758
Freshwater eutrophication	kg P eq	1.63738E-06	1.61841E-06	1.07284E-06
Marine eutrophication	kg N eq	1.38585E-06	1.14163E-06	1.64105E-06
Terrestrial ecotoxicity	kg 1,4-DCB	0.080743453	0.043739996	0.313676442
Freshwater ecotoxicity	kg 1,4-DCB	0.000280339	0.000440004	0.000255346
Marine ecotoxicity	kg 1,4-DCB	0.000386964	0.000624152	0.000520773
Human carcinogenic toxicity	kg 1,4-DCB	0.000413799	0.000225923	0.000329143
Human non-carcinogenic toxicity	kg 1,4-DCB	0.010785289	0.01504744	0.009460733
Land use	m2a crop eq	0.003454371	0.002465401	0.004261077
Mineral resource scarcity	kg Cu eq	3.1721E-05	4.06592E-05	4.39954E-05
Fossil resource scarcity	kg oil eq	0.059796377	0.04733709	0.073290094
Water consumption	m3	0.002925664	0.001845985	0.003520725

TableA.3. ReCiPe midpoint (H) results for the three films for scenario 2.

Impact category	Unit	PET/LDPE	MONO PET	MONO PE
Global warming	kg CO2 eq	0.10654102	0.078488617	0.145644649
Stratospheric ozone depletion	kg CFC11 eq	1.17496E-07	3.01567E-07	1.5535E-08
Ionizing radiation	kBq Co-60 eq	0.001724472	0.000707708	0.001982568
Ozone formation, Human health	kg NOx eq	0.000130985	9.23674E-05	0.000142557
Fine particulate matter formation	kg PM2.5 eq	3.0762E-05	3.83369E-05	2.40131E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.000149199	9.76575E-05	0.000165767
Terrestrial acidification	kg SO2 eq	7.54878E-05	9.50446E-05	5.02645E-05
Freshwater eutrophication	kg P eq	2.74984E-06	2.70687E-06	2.93121E-06
Marine eutrophication	kg N eq	1.41017E-06	1.20341E-06	1.66833E-06
Terrestrial ecotoxicity	kg 1,4-DCB	0.06188295	0.049247767	0.271569216
Freshwater ecotoxicity	kg 1,4-DCB	0.00027117	0.000413754	0.000252079
Marine ecotoxicity	kg 1,4-DCB	0.000361268	0.000590424	0.000487707
Human carcinogenic toxicity	kg 1,4-DCB	0.000444819	0.000283677	0.000362787
Human non-carcinogenic toxicity	kg 1,4-DCB	0.011741092	0.015663301	0.011226697
Land use	m2a crop eq	0.003929854	0.00375617	0.004396294
Mineral resource scarcity	kg Cu eq	4.55512E-05	8.6769E-05	4.72162E-05
Fossil resource scarcity	kg oil eq	0.057631704	0.047491316	0.069460078
Water consumption	m3	0.003145564	0.002160913	0.003813427

Table A.4. ReCiPe midpoint (H) results for the three films for scenario 3.

Impact category	Unit	PET/LDPE	MONO PET	MONO PE
Global warming	kg CO2 eq	0.080648548	0.038661266	0.105801015
Stratospheric ozone depletion	kg CFC11 eq	1.09327E-07	-8.30752E-08	1.17172E-08
Ionizing radiation	kBq Co-60 eq	0.001855608	-0.017912365	0.00185689
Ozone formation, Human health	kg NOx eq	0.000146795	3.65567E-05	0.000159737
Fine particulate matter formation	kg PM2.5 eq	3.83494E-05	3.293E-05	2.85752E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.000165144	3.61633E-05	0.000181734
Terrestrial acidification	kg SO2 eq	9.78934E-05	6.25625E-05	6.52961E-05
Freshwater eutrophication	kg P eq	1.72675E-06	5.46435E-06	7.87524E-07
Marine eutrophication	kg N eq	8.19218E-07	3.09402E-06	9.93653E-07
Terrestrial ecotoxicity	kg 1,4-DCB	0.069763731	0.240736225	0.1192314
Freshwater ecotoxicity	kg 1,4-DCB	0.000204885	0.0001533	0.00020039
Marine ecotoxicity	kg 1,4-DCB	0.000273115	0.000280473	0.000295279
Human carcinogenic toxicity	kg 1,4-DCB	0.000325034	0.000261335	0.0003053
Human non-carcinogenic toxicity	kg 1,4-DCB	0.009336033	0.008743108	0.008775669
Land use	m2a crop eq	0.005480154	0.005183696	0.006669413
Mineral resource scarcity	kg Cu eq	4.53889E-05	0.002072075	4.54028E-05
Fossil resource scarcity	kg oil eq	0.058293555	0.02890156	0.056586547
Water consumption	m3	0.003119234	0.002413789	0.003849322

Table A.4. ReCiPe midpoint (H) results for the three films for sensitivity 1.

Impact category	Unit	PET/LDPE	MONO PET	MONO PE

Global warming	kg CO2 eq	0.111500761	0.049605084	0.099727282
Stratospheric ozone depletion	kg CFC11 eq	1.21116E-07	-3.07729E-07	1.19517E-08
Ionizing radiation	kBq Co-60 eq	0.001761362	0.000934112	0.002147342
Ozone formation, Human health	kg NOx eq	0.000170107	0.000114116	0.000192798
Fine particulate matter formation	kg PM2.5 eq	4.74524E-05	7.4468E-05	5.18761E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.000188198	0.000116159	0.000214331
Terrestrial acidification	kg SO2 eq	0.000139258	0.000217426	0.000133681
Freshwater eutrophication	kg P eq	1.84354E-06	6.94208E-06	3.62595E-06
Marine eutrophication	kg N eq	1.3783E-06	3.17011E-06	7.54353E-07
Terrestrial ecotoxicity	kg 1,4-DCB	0.096832354	0.326298849	0.054405886
Freshwater ecotoxicity	kg 1,4-DCB	0.000241878	0.00037811	0.000179265
Marine ecotoxicity	kg 1,4-DCB	0.000342076	0.000629369	0.000213613
Human carcinogenic toxicity	kg 1,4-DCB	0.000412593	2.92032E-05	0.000290977
Human non-carcinogenic toxicity	kg 1,4-DCB	0.009204501	0.017583685	0.00766195
Land use	m2a crop eq	0.004418364	0.003739379	0.005769403
Mineral resource scarcity	kg Cu eq	3.42137E-05	0.002859827	4.9822E-05
Fossil resource scarcity	kg oil eq	0.055349071	0.030743149	0.057052233
Water consumption	m3	0.002953221	0.0032379	0.003920868

Table A.5. ReCiPe midpoint (H) results for the three films for sensitivity 2.

Impact category	Unit	PET/LDPE	MONO PET	MONO PE
Global warming	kg CO2 eq	0.069015698	0.020767818	0.087900252
Stratospheric ozone depletion	kg CFC11 eq	1.05657E-07	-2.55886E-07	1.00019E-08

Ionizing radiation	kBq Co-60 eq	0.001914524	-0.026277906	0.001800425
Ozone formation, Human health	kg NOx eq	0.000153899	1.14824E-05	0.000167455
Fine particulate matter formation	kg PM2.5 eq	4.17583E-05	3.05008E-05	3.06248E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.000172307	8.53555E-06	0.000188908
Terrestrial acidification	kg SO2 eq	0.00010796	4.79691E-05	7.20494E-05
Freshwater eutrophication	kg P eq	1.2671E-06	6.70322E-06	-1.75579E-07
Marine eutrophication	kg N eq	5.53717E-07	3.94342E-06	6.9054E-07
Terrestrial ecotoxicity	kg 1,4-DCB	0.073304372	0.326767272	0.050789772
Freshwater ecotoxicity	kg 1,4-DCB	0.000175105	3.62844E-05	0.000177168
Marine ecotoxicity	kg 1,4-DCB	0.00023351	0.000141219	0.000208825
Human carcinogenic toxicity	kg 1,4-DCB	0.000271218	0.000251298	0.000279473
Human non-carcinogenic toxicity	kg 1,4-DCB	0.0082555	0.005634036	0.007674483
Land use	m2a crop eq	0.006176666	0.005825049	0.007690669
Mineral resource scarcity	kg Cu eq	4.53159E-05	0.002964024	4.45881E-05
Fossil resource scarcity	kg oil eq	0.058590908	0.02054964	0.050802787
Water consumption	m3	0.003107404	0.002527399	0.003865449

Appendix 4. Results Third Party Review

Ecochain

Ecochain Technologies BV
H.J.E. Wenckebachweg 123
1096 AM, Amsterdam
The Netherlands

TNO – Circular Economy & Environment
L.P Heemskerk and dr. M. Golkaram
Princetonlaan 6
8584 CB Utrecht
The Netherlands

Review report of LCA on packaging films by TNO

Date:	17 Aug 2022,
Author of review:	dr. Lex Roes, Ecochain Technologies
Title of LCA study:	Comparative environmental life-cycle assessment of PET/LDPE, BOPE and BOPET films
Authors of LCA study:	Dr. Golkaram, M., Heemskerk, L.P.

Introduction

This report presents the result of the critical review according to ISO 14040 /14044 of a comparative LCA of a conventional multilayer packaging for dry foods as the reference (e.g. muesli), composed of PET/LDPE, and two alternatives with mono-material, namely BOPET and BOPE films. The goal of the study was to provide conclusions on the environmental performance of both mono-materials to all actors of the plastics value chain but above all the film producers and packaging film designers.

In the first part of this review, some general remarks are made. In the second part some specific remarks are listed, including the response by the LCA author.

General remarks

A draft version of the report was reviewed. Comments and questions were added into the draft report. Comments concerned amongst others selection of LCA-database references, clarifications of statements, addition of tables and/or figures and consistency of terminology. All of these points were further clarified or corrected by the author in the final version of the report.

As described in ISO 14040/14044, the critical review process has the aim to ensure that

- the methods used to carry out the LCA are consistent with ISO14040/14044,
- the methods used to carry out the LCA are scientifically and technically valid,
- the data used are appropriate and reasonable in relation to the goal of the study,
- the interpretations reflect the limitations identified and the goal of the study, and
- the study report is transparent and consistent.

Specific remarks

In the table below, specific reviewer comments are listed, as well as the response and actions of the LCA author.

Comment reviewer	Response TNO	Response satisfactory (Y/N)
P1: BOPE was not mentioned in title	Added	Y
P2: A bit unclear what the primary focus is of the study. In the title of the study you mention BOPET. From this sentence it seems they are all equally relevant.	The reference or incumbent is PET/LDPE and BOPET and BOPE are the alternatives proposed in this project.	Y
P2: You use a lot of abbreviations throughout the study. Make sure they are all explained somewhere...	Done	Y
P2: Suggestion to make textual change: "avoid further conclusions beyond the scope of this study" into: 'to treat the outcome of the study with care'	Done	Y
P7: Introduce Life Cycle Assessment somewhere and the standards that you will use in this study (ISO 14040/14044). This consists of - Goal and Scope - Inventory analysis - Impact assessment - Life cycle interpretation Say you will follow these standards in this study	Added	Y
P7: I don't know Siracusa, but why is this reference used to introduce LCA in general? In your reference list I see they have performed LCA's of packaging. But they are not an LCA authority such as ISO, right?	I used these two papers as they are well known on LCA of specifically packaging.	Y
P9: What is the geographical scope? Is it the Netherlands? Europe? World?	EU. A part (2.2.3 is added)	Y
P9: See previous comment. Introduce ISO earlier. Are ISO 14040 and ISO 14044 covered by this reference?	Done above (chapter 1)	Y
P9: Also the stiffness is important as it determines the thickness of the films. Then it should be part of the funtional unit (you need to quantify it).	It is very difficult to quantify the exact influence of stiffness on the thickness. However, thorough research has been performed by the film producers to ensure equal stiffness. It is not quantified but qualified.	Y
P9: Reference flows and functional unit were in illogical order	Corrected	Y

P9: Mono PET and Mono LDPE were mentioned instead of BOPET and BOPE	Corrected	Y
P12: Some additional explanation would make Figure 3 more clear. E.g. what do all the abbreviations mean / what is 6x1 / 6x6 etc. What do we see exactly?	Added	Y
P12: Would it be an idea to explain somewhere what pyrolysis and glycolysis are and refer to the specific paragraph where you explain this when you first mention pyrolysis and glycolysis? Personally I vaguely know what pyrolysis is, but I am unfamiliar with glycolysis...	Reference already made to 2.2.5. More info on pyrolysis and glycolysis provided there.	Y
P12: What is the relation between the A4-size that you often mention and teh 50 cm2 from the functional unit?	- The A4 size is a rule of thumb in industry which is the standard size above which the films are sorted. Smaller films are not economically reasonable to be recycled at the moment. The FU of 50 is a typcal film size needed for the packaging of muesli - Added this explanation as a footnote.	Y
P14: Change wording: 'the most understood impact category' to 'the most relevant impact category'	Done	Y
P14: Comment on chosen methode: True that ReCiPe is well accepted. But be aware that the new industry standard will become the 'environmental footprint method' by the European Commission.	Indeed! In the future we focus on this method	Y
P16: To me it is not completely clear what the 'yield' refers to and the 'carbon efficiency'. Also, how/when do you avoid products? Perhaps you can explain somewhere (in a general explanation of pyrolysis and glycolysis?)	I added a description of the Yield and carbon efficiency in the text. I suggest that you have a look at the material flow in the appendix at the end of the report for more info.	Y
P16: Suggestion to move 'Data quality requirements' from 'goal and scope' to 'inventory analysis'.	Moved	Y
P17: Suggestion to give some more background / details on the BOPET films Europe consortium who provided all data.	Added names, that should be sufficient.	Y
P18: This is not the right location for Ecoinvent datasets. Only process data should be listed here. However, the study thus nowhere describe the used / applied Ecoinvent references plus motivation for choice. This should be added somewhere. It is part of the inventory analysis.	Reference removed from Table 9. Table with references added in the appendix	Y
P18: Suggestion to specify process names	Done	Y

P18: Question about different values in Tables for processes and materials (e.g. 30,74 in Table 9 vs 30,73 in Table 8 for BOPET)	Rounding error - corrected	Y
P19: Where do I see 'incineration with energy recovery' as described in Table 2?	Added at the end of this section	Y
P19: Please explain how transportation was calculated	We used the Market process and the 300 km is an assumption	Y
P19: Do you apply system expansion / substitution for all the output products? (Refers to Table 10)	We use the avoided product approach (substitution)	Y
P19: "For pyrolysis additional sorting is necessary as the input is highly limited" → Can you explain this statement a bit more? I do not fully follow.	Changed in: For pyrolysis additional sorting is necessary as pyrolysis requires clean streams without sulphur, oxygen or nitrogen containing compounds	Y
P19: Can you indicate how much pyrolysis oil replaces how much diesel? Do they have equivalent function?	Formula added	Y
P19: Express usint electricity in kWh	Done	Y
P19: Specify difference between types of electricity	Specified	Y
P20: Question why Table 11 is expressed per 1,3 kg	- The data is used s received. The feed was 1.3 and therefore the LCI was based on this FU. - The input to pyrolysis plant is 1 kg and there is additional sorting before it goes to pyrolysis with the efficiency of 77%. So (100/77) leads to 1.22 kg input, of which the process energy is based on. The unsorted (0.3 kg is incinerated with energy recovery)	Y
P20: What is 'Anon'?	Changed in 'Eurostat'	Y
P22: Check statements: (0,083/0,154) = 53,9%. So not '53% lower' but '53% of' (and then rounded in fact 54%)	I changed this to focus on both BOPE and BOPET and compare them to PET/LDPE.	Y
P24: Comment to the following statement: "Indeed, the pyrolysis of PET can produce carbon dioxide depending on the temperature of the pyrolysis, nevertheless, this strongly depends on the catalyst and is not always the case" → As this is fossil CO2, it might be significant for the results. Should this be a topic for the sensitivity analysis? The current statement sounds a bit unscientific...	Sentence has been removed	Y
P24: Clarify why PET is mentioned instead of BOPET	The production of material (PET) is the same for PET or BOPET their difference is in the processing. This discussion is for material not processing	Y

Ecochain

P24: Clarify in which processes there are emissions of Methane, bromo-, Halon 1001	Clarified	Y
P24: Explain why BOPE also scores higher on terrestrial acidification and fine particulate matter formation. Is that also due to the Vanadium?	Explained in text	Y
P26: Question: Often catalysts are recycled/recovered. Isn't that the case during/after glycolysis?	It is very hard to recover the metal catalyst I this process. But we do a Sensitivity analysis for different catalysts.	Y
P28: Check order products in graphs	Corrected	Y
P31: Question regarding Figure 4: Is this per FU? Or per kg catalyst? Can you specify? And what does a negative value mean? That you add back to the reserves? That sounds strange...	I added the detailed chart	Y
P32: Statement in conclusions that both BOPET and BOPE are beneficial seems wrong	Corrected. Holds only for BOPET.	Y
P32: Suggestion on phrasing 'upto 103%'	Corrected into 'by 103%'.	Y
P33: Both ISO 14040 and ISO 14044 should be referenced.	Added	Y
P36: Change name 'Appendix 2: Life Cycle Inventory'	Changed into 'Appendix 2: Database references'.	Y
P36: 1) You use several databases simultaneously. Why not everything Ecoinvent? And why a US database (USLCI)? The geographical scope is Europe, right? 2) I think you should explain this somewhere….!	1) We have studied the accuracy of each process at TNO. Ecoinvent is not accurate in many cases. For the plastics Industry 2,0 is the most up to date. For the recycling we use the only recycling process in Sima Pro which is from USLCI and then changed the geography (electrccity grid and distances) to the EU geography 2) Explanation added	Y
P36: Aluminium is not the same as aluminium oxide… For Aluminium oxide there are different references	Correct I change this to Aluminium. The material used is aluminium and in the process of mellaizidng in turns into AloX so the input is Al and not AlOx	Y
P37: It is common that you add In the dataset table a column for remarks. For example to explain why you think that Boron carbide is representative for Boron Nitride	Added	Y
P37: Three different trucks are used. Is this explained somewhere?	Explanation added	Y
P37: Why different datasets for electricity?	We used the data from USLCI. And updated them to EU geography in terms of electricity and transportation. Since the heat generation from Diesel and LPG and gas were based on volume due to lack of accurate density, LHV and carbon content we did not switch to Ecoinvent heat generation process which is based on kwh/MJ. Annex 4 of the attached ref. also uses similar approach.	Y

	environmental_savings_from_plastic_waste_recycling_-_jrc_report_-_v9	
P38: Why different datasets for Heat and why also US data?	Same comment as above. Since the combustion technology is not different from US we kept them as it is.	Y
P39: Natural gas from North America? Why?	Same comment as above on combustion.	Y
P40: Why different datasets for heat recovery?	Please find the attachment: pbl-2019-klimaat-en-energieverkenning-2019-3508 8176_defrapportMO_1398939619 afvalverwerking-in-nederland-gegevens-2018-def-09-03-2020	Y
P41: What is the source of these efficiencies?	References are added. Please find the attachment: pbl-2019-klimaat-en-energieverkenning-2019-3508 8176_defrapportMO_1398939619 afvalverwerking-in-nederland-gegevens-2018-def-09-03-2020	Y

Conclusions and recommendation

The LCA study under review has been performed thoroughly and accurately. Sufficient work has been put into the gathering of actual foreground data. For other data, LCA databases were used. Proper databases (Ecoinvent, USLCI and Industry 2.0) were selected for this. Details of the life cycle and the choice of reference data to model the life cycle have been clearly described. An appropriate impact assessment method (Recipe) was selected for the calculations. Sufficient interpretation of the results was done to check the validity of the results and fulfill the scope of the study.

Therefore, my conclusion is that the LCA report complies with the ISO 14040/14044 norm, which ensures quality and transparency of the LCA. However, the correctness of the calculations remains the responsibility of the LCA practitioner (TNO).