LIFE CYCLE ASSESSMENT + SUSTAINABILITY POTENTIAL

PLASTIC ALTERNATIVES

one • five

As the first European venture capital fund, Planet A relies on its own scientific team to assess the environmental and climate impact of an innovation. Prior to an investment, a life cycle assessment, like this one, is conducted and integral part of the investment decision. All assessments as well as the methodology are published for maximum transparency.

Terminology and abbreviations

CED_f	Cumulative fossil energy demand
CO_2-eq.	Carbon dioxide equivalents
DAC	Direct air capture: a process to extract CO2 from the atmosphere
EOL	End-of-life
EPS	Expanded polystyrene
FU	Functional unit: Quantified performance of a product system for use as a reference unit
GHG	Greenhouse gas
GWP	Global warming potential
HDPE	High-density polyethylene
LCA	Life cycle assessment
LCI	Life cycle inventory
LDPE	Low-density polyethylene
MSW	Municipal Solid Waste Incineration
PBS	Polybutylene succinate
PE	Polyethylene
PEF	Polyethylene furanoate
PET	Polyethylene terephthalate
PHA	Polyhydroxyalkanoate
PHB	Polyhydroxybutyrate
PLA	Poly lactic acid
PP	Polypropylene
PPT	Polypropylene terephthalate
PUV	Polyurethane
PVC	Polyvinyl chloride
PS	Polystyrene
PtX	Power-to-X: synthesis processes providing numerous products using (renewable) electricity
Sb	Antimony
TPS	Thermoplastic starch
WSI	Water stress index

About one.five

one.five's vision is to remake single-use plastic packaging and extend the life cycle of reusable packaging systems. Breakthroughs in bio-based materials research have created the possibility for a completely transformed packaging industry. With their approach, one.five is not just targeting a specific solution but building a platform for cleaner and circular packaging systems. Stricter regulations and changes in consumer demand are forcing change into the packaging value chain, which includes large corporations from the FMCG (fast-moving consumer goods) sector. one.five wants to use this momentum to develop sustainable packaging systems for a wide variety of product applications as the preferred solutions provider for the entire materials value chain.

Summary

The current use of plastics results in severe negative impacts on the environment. Alternative, more sustainable solutions are urgently needed.

Part I of this report provides an exemplary simplified **Life Cycle Assessment (LCA) of a packaging alternative currently developed by one.five**. **The LCA shows a substantial impact reduction potential of the one.five packaging alternative over the conventional PET-based composite solution**. In an end-of-life (EOL) recycling scenario, one.five has the potential to reduce about 37% in GHG emissions per functional unit. **If the end-of-life scenario is not included in the calculation, the one.five alternative has at least 75 % less negative impact in terms of packaging production and raw material extraction than the PET-based counterpart in four out of five impact categories.** The LCA helps to highlight environmental hot spots and, from a systemic perspective, to identify the most suitable EOL-treatment for both packaging solutions. It underlines the high significance of EOL treatment for packaging. In conclusion, **LCA proves to be a well suited tool for one.five to develop environmental-friendly packaging solutions most suitable for EOL treatment systems on existing as well as new markets.**

Part II provides **insights into today's plastic industry and negative impacts of current plastic production, use and end-of-life (EOL)**. Plastic production, use and EOL are a **major emitter of GHG emissions**. GHG emissions emitted by the plastic industry are still increasing. Additionally, **the current system negatively impacts human health and biodiversity**. Plastics contain thousands of harmful chemicals. Due to dysfunctional EOL systems **plastics leak into the environment**. As a consequence, plastics can be found everywhere on this planet. In order to change for the better, a profound change is needed in the industry. This requires changes in how the industry works, new legislation as well as more research activities. Holistic approaches are needed that incorporate sustainability considerations in material design and manufacturing. **one.five can act as a catalyst in this space by bridging the gap between research and wide-scale commercialization of more sustainable alternatives to conventional plastics.**

Table of content

1. About this study

one.five develops and scales sustainable alternatives to conventional plastics. In the next few years, one.five will develop and promote a multitude of novel sustainable materials. These materials will eventually reduce the amount of conventional plastics needed. one.five uses life cycle assessments (LCAs) as a tool to identify the most sustainable alternatives to conventional plastics. They focus on reducing plastic waste pollution and decreasing emissions from packaging over the whole life cycle. The end-of-life (EOL) of these alternatives is thus of great importance. one.five develops products in accordance with (non-)existing waste treatment solutions and product use cases in the targeted markets. Biodegradability in the natural environment plays an important role in most packaging alternatives one.five develops.

Since the materials that one.five will offer its customers are still in development, this report is meant to provide insights into the potential benefits of working with an eco-design process and tool that identifies the most sustainable material options for the given application and market. This report is structured in two main parts:

- Part I (chapter 2) provides an exemplary simplified LCA of a paper-based alternative to the existing single use PET-based composite sachet, which is currently under development by one.five. The report demonstrates how LCA can be used to identify environmental hot-spots as well as the most sustainable alternatives to conventional plastics.
- In part II (chapter 3), we provide an overview of plastics currently used as well as their negative effects and discuss sustainable alternatives and their impact.

To conclude, potential ways to improve the present, dysfunctional system are briefly discussed in section 4.

2. Part I - Exemplary LCA

one.five develops and deploys sustainable packaging solutions in their customers' product value chains. one.five uses Life Cycle Assessments and eco-design principles to identify the most suitable packaging alternatives for a given application in a chosen market. We conducted an exemplary, simplified, and comparative LCA for one potential one.five packaging solution and its conventional counterpart. The aim is to demonstrate how to measure the full scope of a packaging solution's impact. With the help of an LCA, environmental hot-spots for two different packaging solutions can be identified and compared. Thus, one.five can develop new materials benchmarking the environmental impact of the customer's existing packaging material. Consequently, necessary improvements to the material that will contribute positively to the protection of the environment can be scaled up faster. LCAs are a powerful tool to get a holistic ecological footprint of a product or service beyond just greenhouse gas (GHG) emissions.

We conducted a **simplified LCA for 100 paper based single-use shampoo sachets**, which can replace the existing primary packaging solution of 100 PET-based composite sachets. To include the influence of one.five products on the packaging system we apply a **consequential LCA approach**.

2.1. Functional unit and assessed indicators

The functional unit (FU) is ***100 sachets with a volume of 6 ml to contain liquid ingredients*** used to sell shampoo.

The system is assessed using the following indicators

- **climate change** (Intergovernmental Panel on Climate Change (IPCC) 2014)
- **abiotic resource depletion** (CML - Department of Industrial Ecology 2016)
- **cumulative fossil energy demand** - CED_f (Verein Deutscher Ingenieure (VDI) (ed.) 2012)
- **land use**
- **water demand** - WSI (Pfister, Koehler, and Hellweg 2009).

2.2. Data origin and quality

As one.five is an early stage startup and this LCA only serves as a simplified example, most data derived from the ecoinvent database version 3.8 or literature. Nevertheless, one.five collected some inventory data about production material and respective amounts from business partners within a questionnaire. The LCA calculations were partly conducted within the software OpenLCA.

2.3. Description of the supply chain elements

The LCA comprises a comparative LCA for two different packaging solutions: a conventional PET(polyethylene terephthalate) based composite sachets and the paper-based one.five alternative.

The ***conventional PET-based composite sachets*** are produced using fossil resources. While there is a well established recycling scheme for drinking bottles made of PET in many countries (BVSE 2020), there is no recycling scheme for other PET-based products, especially PET-Aluminium-LLDPE composites frequently in use in the industry. At present, only a minor share of plastics is recycled. The majority ends up in landfills and in nature or is incinerated (see section 3.1.3).

one.five develops a ***paper-based sachet alternative*** wrapped with a biodegradable coating, the so-called ***one.five layer***. The paper frames and stabilizes the sachet while the one.five layer provides the additional barrier properties needed to contain and protect the liquid product. The one.five layer has been designed to ensure recyclability should the material end up in the paper waste stream. However, the final product (single-use shampoo sachets) may end up in the natural environment rather than in the paper waste stream due to consumer negligence, so biodegradability in soil and marine environments will be certified as well.

Figure 1 shows the process steps of both packaging solutions. The LCA starts with the production processes of the respective raw materials and the energy needed to manufacture the sachets. The need for secondary or tertiary packaging material, transport processes after production and the use phase of the sachets is assumed to be the same in both cases and thus not part of this LCA.

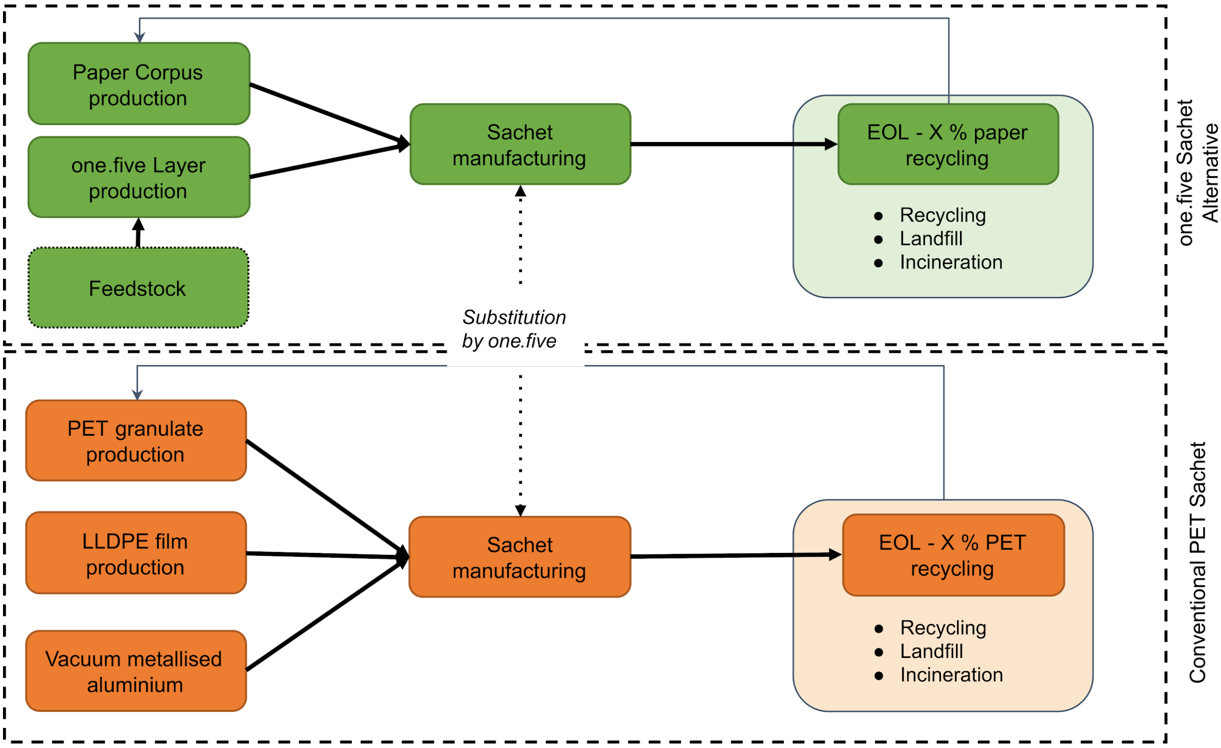


Figure 1 *Depiction of system boundaries. Green processes show the life cycle stages of the one.five packaging alternative, while orange processes represent the life cycle stages of the existing PET-based composite packaging solution. LLDPE: Linear low-density polyethylene.*

For one.five the end-of-life ***(EOL)*** is very important as the improvement of this life cycle phase is a core element of their business model. In some countries like Germany, there is a separate collection system ("Gelber Sack") for plastic waste. 17% of this separately collected plastic waste in Germany is recycled, 73% is treated (e.g. incineration or landfilling) and 10% is exported to third countries. Of exported waste, 76% is recycled, 14% is landfilled, 7% incinerated and 3% is lost to the environment due to inadequate handling (Bishop, Styles, and Lens 2020). The non-separately collected waste ends up in municipal solid waste and is treated according to the municipal solid waste treatment in Germany and the EU. Figure 2 gives an overview about the possible plastic waste flows.

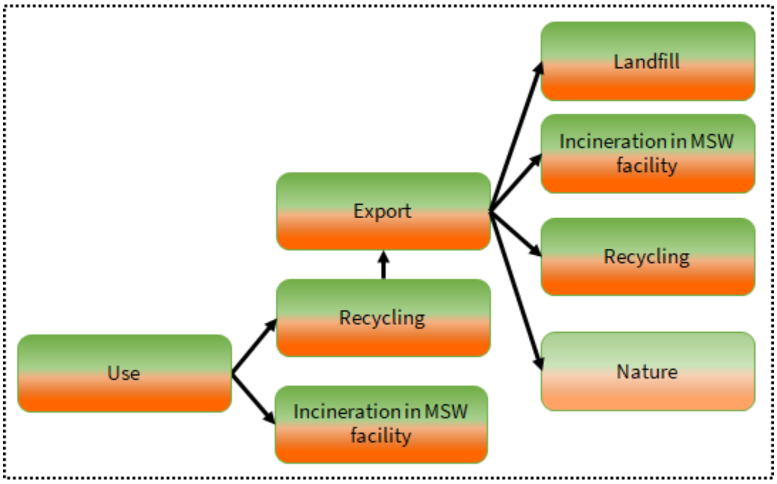


Figure 2 *Depiction of the EOL of all plastic products. Abbr.: MSW – municipal solid waste.*

However, there is a high degree of uncertainty in waste statistics. Studies reveal that the share of plastics converted into recycled material is much lower than claimed in official statistics (Wecker 2018). For example, Eurostat reports a recycling rate of 69.9% for packaging waste in Germany in 2017 (Eurostat 2020). However, this number is calculated as the share of plastic that is fed into the recycling system. The number does not give an indication of the production of recycled plastic, i.e. the output. Another study estimates that in 2017, the actual recycling share (defined as recyclate produced per plastic waste arising) were 30% and 17% of the total and post-consumer plastic waste in Germany, respectively (Conversio Market & Strategy GmbH 2018). A similar share is reported in (Plastic Recyclers Europe 2019). Others report even lower numbers: 11% of plastic waste in the EU is recycled to replace virgin material according to (Hsu, Domenech, and McDowall 2021).

In order to account for these uncertainties, we would usually assess different scenarios in a detailed sensitivity analysis. As the goal of this simplified comparative LCA is to demonstrate the impact assessment of different packaging solutions and to show how to identify environmental hot-spots, no detailed sensitivity analysis is being conducted here. Instead, we included the following scenarios to get an idea of the EOL impacts to both alternative packaging systems:

1. The worst case: no recycling, i.e. either incineration in a municipal solid waste incineration (MSW) or landfill. We define two sub-scenarios here:
   a. 100 % MSW (R1a-MSW),
   b. 100 % landfill (R1b-LF).
2. The best case: defined as 100 % recycling (R2-100).
3. The German case introduced above, which would be a mixture of MSW, Recycling and Landfill (R3-DE).

The consequential LCA approach includes the assessment of environmental impacts of substituted products or activities. In the one.five case this is especially relevant when it comes to the end of life processes. For example, municipal solid waste (MSW) produces energy, which substitutes other primary energy sources. Another one is recycled material that substitutes virgin material (Wernet et al. 2016). When emission savings from substitutions are higher than the negative impact caused by the treatment process itself, EOL reduces the overall emissions of the product. If emission savings are lower than the negative impact caused by the treatment process, EOL increases the overall product's negative impact.

Consequential LCAs contain certain market assumptions. In this study, we look at the European market. Only where European data is not available, we refer to the German market and indicate that accordingly.

An overview of the Life Cycle Inventory (LCI) for both packaging alternatives including the recycling scenarios is being provided in Tables A.1 and A.2 in the Annex. All processes except the one.five-layer are taken from the ecoinvent database version 3.8 (Wernet et al. 2016).

2.4. Results and discussion

Taking emissions from sachet production and raw material extraction into account, the one.five sachets perform substantially better than the conventional PET-based counterpart in four out of five impact categories. The one.five sachets reduce the negative environmental impacts in these four categories at least by 75 % (see figure 3). The largest driver for these reduction potential of environmental impact results from the switch of fossil based plastics to a bio based solution.

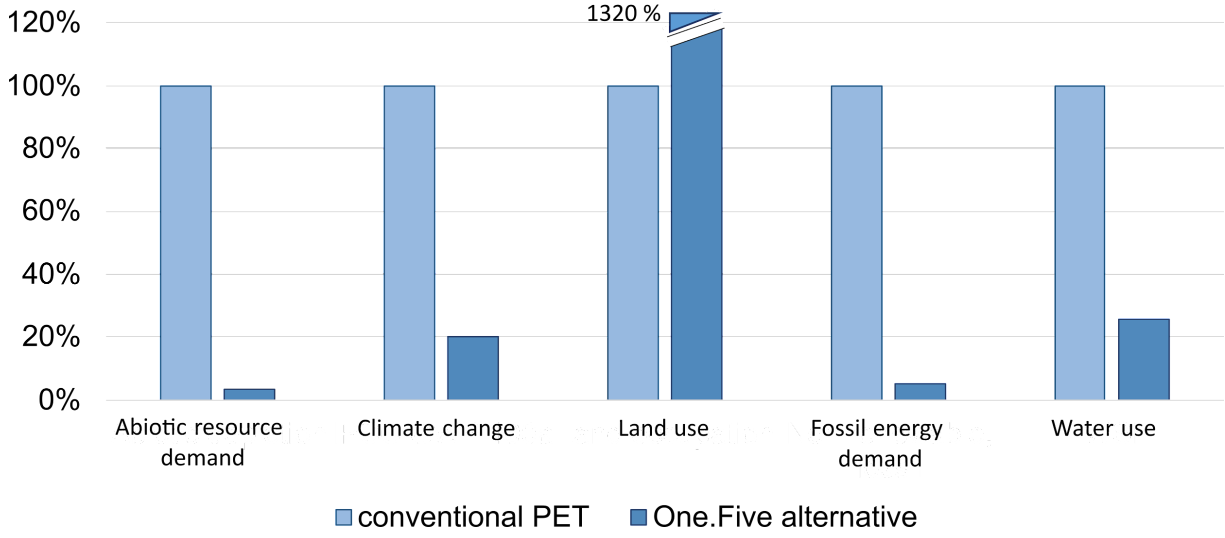


Figure 3 *Comparative results of the environmental impacts from sachet production* <u>*without EOL*</u>

While the kraft paper production is the main driver for environmental impact of the one.five solution, PET is the main driver for the counterpart. Compared to kraft paper production, the production of PET has a significantly higher ***abiotic resource demand,*** measured in Antimony (Sb) equivalents. This refers to the depletion of non living resources such as fossil fuels, minerals, clay, or peat. Consequently, the switch from fossil resources to renewable ones reduces the negative impact within this impact category. The ***fossil energy demand*** (MJ) and the ***water use*** (m^3) is also lower for kraft paper production than for PET. ***Land use*** (occupied area in m^2) is the exception. This is usually the case for material production from renewable virgin feedstock where the land use indicator is higher than for the production of materials from fossil resources. Possibilities to reduce the amount of land use is the use of residues and a high amount of recycling (see Table 1). Due to lack of data the land use for the feedstock of the one.five layer is not included, yet. one.five is aware of the land use impact and is planning to use residual waste as feedstock for the layer production. Nevertheless, indirect land use might still occur as one.five will replace current use cases for these residues (e.g. incineration producing energy). Suppliers will need to replace the previously used residue - this primary feedstock is then responsible for further land use.

As Table 1 reveals, a high degree of recycling has a positive effect on all impact categories including land use. In Europe the recycling quota of paper is about 74 % (EPRC 2020), which is much higher than the one for PET packaging and the one assumed in the German market scenario (R3-DE). The higher the recycling rate of paper, the less negative impact regarding land use, as less pulp for paper production has to be produced.

In a systemic perspective, MSW or recycling are the best choice for the EOL treatment of the one.five sachets. The colors within Table 1 and 2 display the highest impact reduction potential (green) for one impact category to the lowest (red) in absolute values. Positive values mean that the EOL treatment generates additional negative impact. Note that the impact categories are not comparable with each other due to different units.

Table 1 Comparison of the impacts for the EOL scenarios - **one.five sachets.**
R1a-MSW: 100 % Municipal Waste Incineration, R1b-LF: 100 % landfill, R2-100: 100% recycling, R3-DE: German plastic EOL-split

Impact category	Reference unit	R1a-MSW - 100 % Municipal Waste Incineration	R1b-LF - 100 % landfill	R2-100 - 100% recycling	R3-DE -German plastic EOL-split
Abiotic resource demand	kg Sb-eq	-1.90E-08	1.06E-08	-1.08E-08	-1.65E-08
Climate change	kg CO_2 -eq	-4.26E-02	1.01E-01	-3.21E-02	-3.79E-02
Land use	m^2a	-4.81E-02	3.76E-04	-2.68E-01	-1.01E-01
Fossil resource demand	MJ	-4.45E-01	2.30E-02	-5.26E-01	-4.57E-01
Water use	m^3	-2.03E-02	1.09E-04	-1.73E-02	-1.92E-02

Table 2 Comparison of the impacts for the EOL scenarios - **conventional PET-based composite sachets**
R1a-MSW: 100 % Municipal Waste Incineration, R1b-LF: 100 % landfill, R2-100: 100% recycling, R3-DE: German plastic EOL-split

Impact category	Reference unit	R1a-MSW - 100 % Municipal Waste Incineration	R1b-LF - 100 % landfill	R2-100 - 100% recycling	R3-DE -German plastic EOL-split
Abiotic resource demand	kg Sb-eq.	-4.68E-08	1.52E-09	3.35E-06	7.90E-07
Climate change	kg CO_2-eq.	7.14E-02	5.96E-03	-7.80E-02	3.36E-02
Land use	m^2a	-7.07E-02	3.08E-04	-1.75E-02	-5.64E-02
Fossil resource demand	MJ	-6.53E-01	1.74E-02	-2.13E+00	-1.00E+00
Water use	m^3	-3.00E-02	4.96E-05	-7.56E-03	-2.39E-02

The most suitable EOL treatment for the PET-based composite sachets varies among the impact categories (see Table 2). Regarding landfill as an EOL option (R1b-LF), no negative impact from mismanagement has been included: impact factors do not consider the negative effects of marine littering and animals suffering from plastic waste in the oceans. Including this specific negative impact is likely to make landfill as EOL treatment even worse than stated in the results of this LCA. Although PET recycling has a mainly positive effect, this is an unlikely case due to a lack in recycling systems and technology for composite packaging.

Figure 4 shows the global warming potential (GWP) in kg CO_2-eq. per FU for the one.five alternative and the PET-based composite sachets. The FU has been defined as ***100 sachets with a volume of 6 ml to contain liquid ingredients*** (see section 2.1).

The light-blue bars indicate the contribution of the one.five production components to the overall impact. These components are summed up to the entire raw material and production impact (dark-blue bars). The impact of the one.five EOL-scenarios (blue-shaded bars) has been included in the net results. The **yellow dots show the net results** of the one.five packaging alternative in each scenario. The contribution of the components of the PET-based composite sachets to the overall impact is not indicated separately. Equivalent to the one.five sachets, the net results are presented by the **black triangles.**

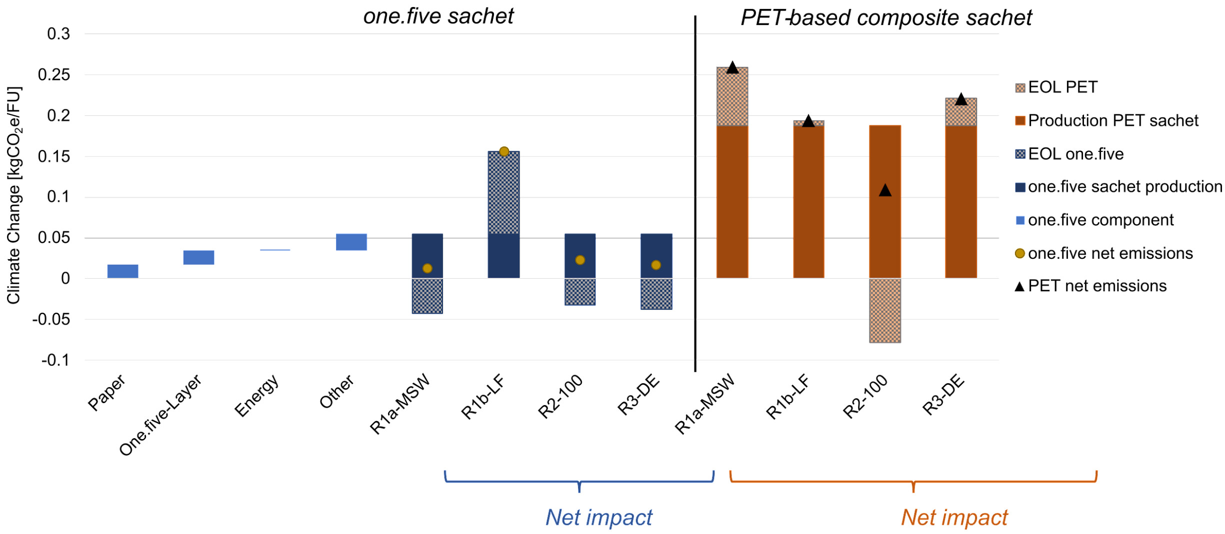


Figure 4 *Depiction of the EOL of all plastic products. Abbr.: MSW – municipal solid waste. R1a-MSW: 100 % Municipal Waste Incineration, R1b-LF: 100 % landfill, R2-100: 100% recycling, R3-DE: German plastic EOL-split*

In all EOL scenarios the one.five sachets perform better than the PET-based composite sachets. The PET-based sachets perform best within the recycling scenario (R2-100), but the negative impact is still three times higher than for the one.five sachets.

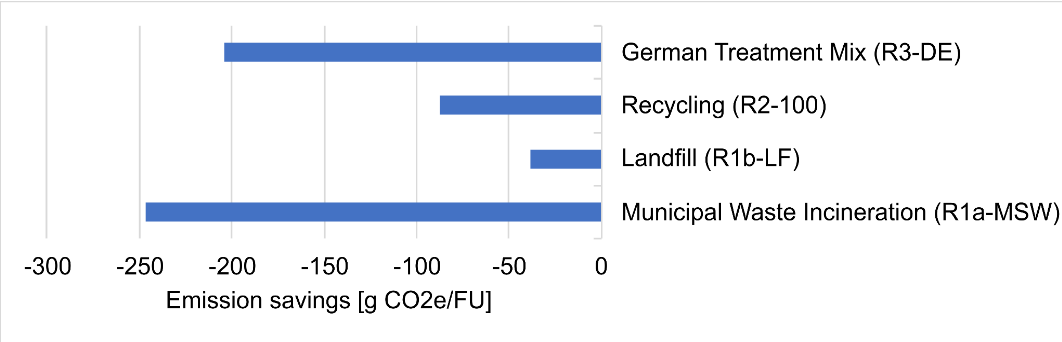


Figure 5 *Systemic emission savings within all EOL scenarios. Abbr.: MSW – municipal solid waste. R1a-MSW: 100 % Municipal Waste Incineration, R1b-LF: 100 % landfill, R2-100: 100% recycling, R3-DE: German plastic EOL-split*

Figure 5 shows the emission reduction potential of 100 one.five sachets replacing the PET-based composite in the market within each EOL scenario. The potential varies from about **40 to 246 g CO_2e per FU**. Interpreting the results (Figure 4 and 5) one should keep in mind that within the whole market **none of the scenarios except for the R3-DE scenario are likely to materialize** as - at least in the mid term - the EOL of packaging will be a split of treatment options, not only because it partly depends on end-consumer behavior.

It is also worth mentioning that one.five focuses on primarily delivering circular solutions to ensure material re-use in regions where recycling/material recovery systems exist. To account for global product portfolios, however, one.five incorporates the appropriate level of natural degradability to ensure materials do not cause harm in markets where little or no recycling systems exist or where the product is so disposable that consumer behavior gets in the way of materials recovery (i.e. high risk of littering).

2.5. Using LCA to support environmental decision making for the packaging industry

This exemplary, simplified LCA helps to highlight environmental hot spots. First, these hot-spots can originate from the production of packaging material. It thus helps to decide on the most suitable material. Second, it helps to identify the importance of the use phase or EOL treatment. In this example the use phase would be the same for both packaging alternatives and has been excluded from the LCA, but it might be very relevant where switching the packaging solution would result in a change in use case. For the one.five sachets, the LCA underlines the significance of the EOL treatment and helps to identify the most suitable one. Thus, packaging solutions already developed can be offered to the right customers and purchased on markets with an adequate EOL treatment. This also proves that the one.five solution can fulfill what it has been designed for. And that Life Cycle Assessments are a well suited tool for one.five to support their decision making in the development of packaging solutions.

3. Part II - Sustainability potential of plastic alternatives

The following section sheds light on current plastic uses, potential alternatives and on the severe negative impacts of the current industry practices[1].

3.1. Conventional plastics and their substitutes

The following section discusses most commonly used plastics and potential alternatives as well as sustainability considerations.

3.1.1. Conventional (petroleum-based) plastics

Conventional plastics made from petroleum are by far the most common type of plastic. Estimates range from around 350 to 400 Mt of conventional plastics produced in 2015 (Cabernard et al. 2022; Rikhter et al. 2022). The biggest market is Asia, where 65% of the global plastic production took place in 2015. Asia also sees the highest plastic consumption (53%). Europe is a net importing region: in Europe, 12% of the global plastic production takes place and 18% of plastic is used. Plastics are used in a sheer endless number of applications. The largest share of plastic is used in packaging applications (Figure 6).

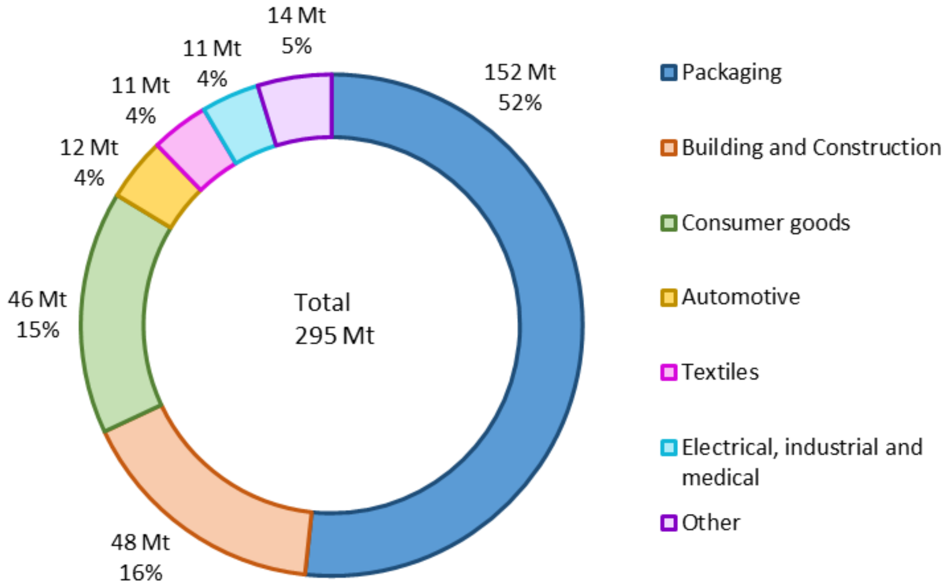


Figure 6 *Global plastic use by sector in 2020. Data taken from (Feber et al. 2022).*

The current demand for plastics is projected to increase substantially in the next decades: by 2050, the global plastic demand is expected to exceed 1100 Mt by 2050 (World Economic Forum, Ellen MacArthur Foundation, and McKinsey & Company 2016). The growing demand for plastics poses serious threats to the environment as long as present negative impacts are not overcome (see below). An overview on the quantities of plastics used in the EU is presented in Figure 7. The most common uses in packaging of these plastics are shown in Figure 8.

[1] This review gives a broad overview on the topic and is not meant to be exhaustive.

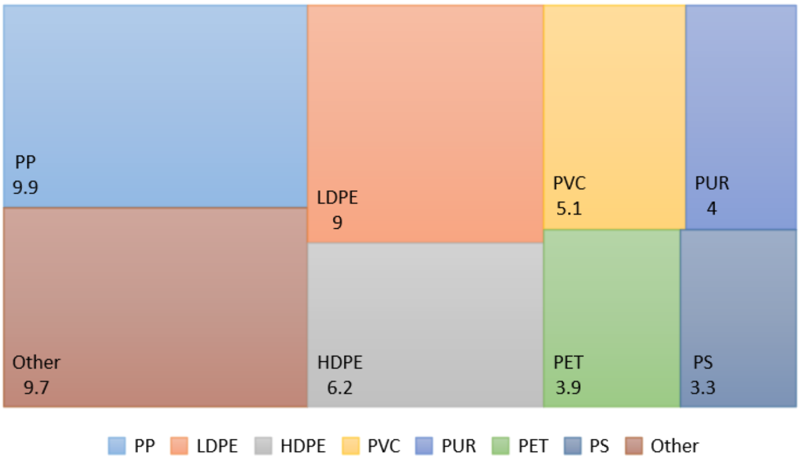


Figure 7 *Processed plastic volume by type in the EU om 2018. Values in Mt. Own depiction based on data provided in (Vanderreydt et al. 2021). Abbr.: PP - polypropylene, LDPE - light density polyethylene, HDPE - high density polyethylene, PVC - polyvinyl chloride, PUR - polyurethane, PET - polyethylene terephthalate, PS - polystyrene*.

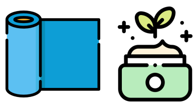
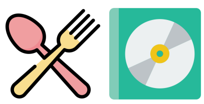
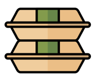
PET		Plastic bottles, biscuit trays, salad dressing container, salad domes
HDPE		Thin plastic bags (used for vegetables and fruits in many supermarkets), shampoo bottles, freeze bags, juice bottles, chemical and detergent bottles
PVC		Commercial cling wrap, cosmetic containers
PP		Microwave dishes, potato chip bags, ice cream tubs
LDPE		Squeeze bottles, rubbish bags, shrink wrap
PS		Plastic cutlery, CD cases, water station cups
EPS		Hot drinks cups, Foamed take-away trays and clamshells
Other		Water cooler bottles, flexible films, multi-material packaging

Figure 8 *Main conventional plastic raisins and their key packaging applications. Adapted from (World Economic Forum, Ellen MacArthur Foundation, and McKinsey & Company 2016). The attribution to the icons's authors can be found at the end of the document (Table A.3).*

3.1.2. Substitutes for conventional plastics

There are many alternatives to conventional, fossil-based plastics[2], including bio-based materials (Table 3). There are many synthesis routes to synthesize plastic monomers or polymers from biogenic feedstock. Most commonly starch or sugar plants are used as feedstocks, such as maize or sugar cane. From a sustainability standpoint it is desirable to use feedstock that does not compete with food and feed production. For instance, hemicellulose and cellulose can be liberated from organic residues and further processed to sugar monomers. These sugar monomers can be subsequently converted into the desired molecules.

Table 3 *Bio-based alternatives to a selection of most commonly used fossil-based plastics (Vanderreydt et al. 2021). Abbr.: All abbreviations listed on page 2.*

Fossil based plastics	Equivalent or approximate biobased alternative
PP	Bio-PP, Bio-PPT, PLA, PHA, PHB, TPS, cellulose-based
LDPE and HDPE	Bio-PE, PLA, PHB, PHA, starch- and cellulose-based polymers, PBS
PS	PLA, PHA, TPS, cellulose-based polymers
PET	Bio-PET, PEF
PVC	Bio-PVC, PHA, starch- and cellulose-based polymers
PUR	Bio-PUR

In addition to biogenic material, plastics (and its precursors) can be synthesized using carbon dioxide and hydrogen. Carbon dioxide can be obtained from point sources, such as biogas upgrading plants, industrial processes, power plants etc., and from the air using direct air capture (DAC). There are multiple ways to produce hydrogen, e.g. electrolysis, pyrolysis, biological processes etc. Synthesis processes allow the production of all hydrocarbon molecules. Often, these processes are called Power-to-X processes due to the use of (sustainably produced) electricity to obtain hydrogen and carbon dioxide.

Another category of plastic alternatives are non-plastic materials that fulfill similar functionalities, e.g. starch or cellulose-based polymers, paper and coated paper, cf. (Shafqat et al. 2020; Guan et al. 2020; Nechita and Roman (Iana-Roman) 2020; Wang, Yang, and Wang 2003; Sid et al. 2021). Natural polymers are often fully biodegradable in nature.

From a sustainability perspective, several aspects are of key importance with regards to the production of plastic alternatives:

- *Feedstock supply:* The supply of biogenic feedstock potentially competes with food and feed production for land. Additionally, the cultivation of biomass requires (mineral) fertilizers resulting in potentially harmful emissions (production and use). If land is used solely to produce bioplastic feedstock, any additional demand for such feedstock might result in land-use change.

[2] The nova institute provides a comprehensive graphic depicting potential plastic alternatives and precursors, as well as a market overview on plastic alternatives. The reader is referred to this document for further details (last accessed on July 21 2022).

The use of residues that one.five aims for is less prone to land-use change and allows the joint production of feedstock for plastic production and biomass for other uses, e.g. food and feed. DAC units and (electrolytic) hydrogen supply require large quantities of electricity. There are many competing markets for electricity and hydrogen from renewable sources, such as the decarbonization of the power sector, the heavy industry and the transportation sector. Substantial additional capacities of renewable energy supply are needed and sectors in which the use of sustainably produced energy is most impactful should be prioritized.

- *Feedstock conversion and plastic production:* The conversion of primary feedstock to desired molecules might be highly energy intensive and/or involve harmful chemicals. The energy demand and requirements for other materials and chemicals is highly process dependent.

3.1.3. EOL of conventional plastic and its alternatives

At present, only a minor share of plastics is recycled. It is estimated that since 1950, less than 10% of plastics have been recycled (d'Ambrières 2019). The remainder has ended up in landfills, in nature or was incinerated. The vast majority of plastics is poorly managed and poses severe risks to the environment.

Often, alternative plastics and non-plastic substitutes for conventional plastics are categorized according to their EOL characteristics (Figure 9). The suitability of plastic materials to different EOL options is not dependent on the primary feedstock. For example, there are biodegradable bio-based and fossil-based plastics, as well as non-biodegradable plastics, regardless of the feedstock. The recyclability of material does not just depend on the material characteristics, but also the characteristics and design of the plastic product (e.g. mono-materials vs. composites) as well as the waste collection (sorted vs. mixed wastes).

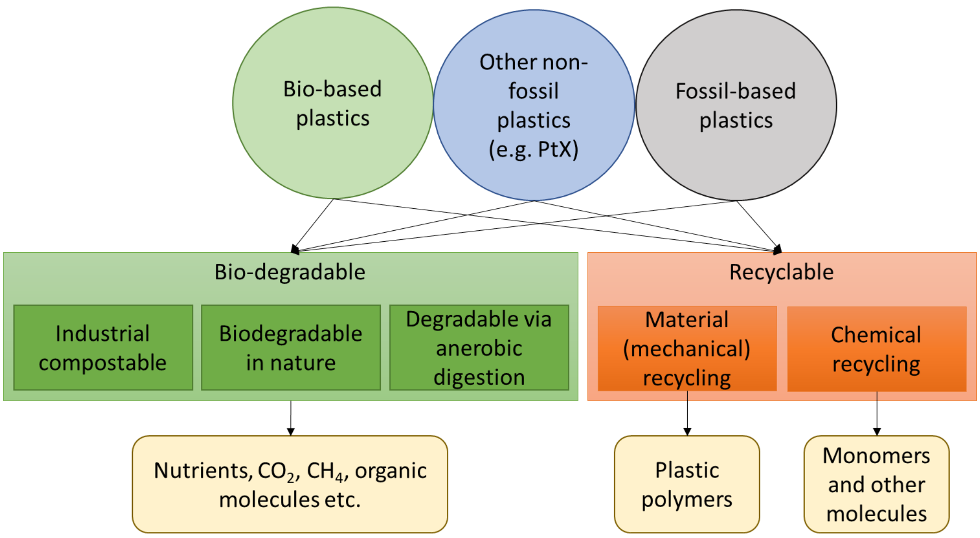


Figure 9 *Broad overview of plastic types and potential EOL options. Other EOL options, e.g. re-use, incineration and landfilling, are not depicted. Abbr.: PtX - Power-to-X.*

So far, non-fossil based plastics only play a minor role in the plastics industry. In 2021, only 2.42 Mt of these plastics were produced (European bioplastics e.V. 2022). The European bioplastics e.V. claims that

35.8% of these materials are bio-based and non-biodegradable, whereas the remainder is biobased and biodegradable. There is no further specification on the biodegradability of the material. Not all materials labeled “biodegradable” degrade in nature. Certain materials need specific conditions to degrade (Ghosh and Jones 2021).

3.2. Environmental impacts of conventional plastics and its substitutes

The production of plastic relies on fossil resources and energy carriers, the production and EOL emits GHG emissions and plastic pollutes the environment and poses a threat to many species. In the following section, these impacts are briefly described. It should be noted that these impacts cannot and should not be considered isolated from other negative impacts of human activities: plastic pollution, for instance, exaggerates negative impacts of climate change or other stressors causing biodiversity loss. Plastic pollution makes many negative impacts worse and the increasing use of plastics amplifies climate change and biodiversity loss. Plastic use and pollution resulting from it is thus a stressor that simultaneously acts on many impact dimensions. The following section gives a brief overview on these impacts. There is extensive literature on these impacts and more information can be found in the cited literature.

3.2.1. Resource use

Conventional plastics use between 4 and 8% of the global mineral oil consumption (Cabernard et al. 2022; Rikhter et al. 2022). In addition to mineral oil, considerable quantities of other fossil energy resources are used as a feedstock and to supply the energy needed to produce conventional plastics (Figure 10). Yet, comprehensive studies assessing the potential implications of wide-scale production of non-fossil based plastics on resource use are scarce.

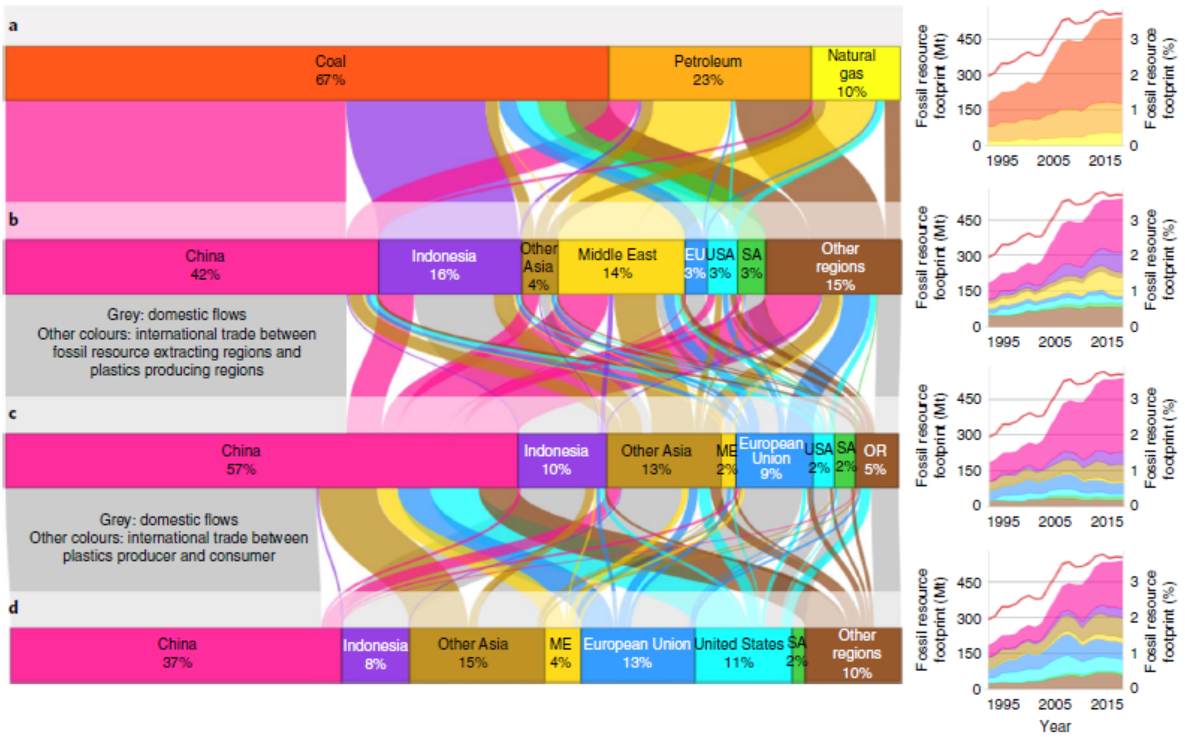


Figure 10 *Value-chain analysis of the fossil resource footprint of global plastics production, including the extraction of fossil resources used as a fuel and feedstock for plastics production. a–d, The sum of each horizontal bar of the flow chart on the left refers to the fossil resource footprint of global plastics production in 2015 (540 Mt in 2015, 100%) and allocates it to the different perspectives in the global value chain: type of extracted fossil resource (a); region*

where fossil resources are extracted (b); region where fossil resources are used for plastics production (as fuel or feedstock) (c); region where plastics are consumed (d). The small graphs on the right show the temporal evolution of the fossil fuel footprint of global plastics production for each perspective (a–d) over the past two decades. The colors of the graphs on the right correspond to the bars of the flow chart. The red line in each represents the global share. EU, European Union; ME, Middle East; SA, South Africa; USA, United States; OR, other regions. Figure and caption were taken from (Cabernard et al. 2022). The content is licensed under a Creative Commons Attribution 4.0 International License.

3.2.2. Climate change

In 2015, the global life cycle GHG emissions of conventional plastics amounted to around 1.8 Gt CO_2-eq. (Zheng and Suh 2019). These emissions corresponded to nearly 4% of the global GHG emissions in 2015. The production of plastic used in the EU accounted for 254 Mt CO_2-eq. emissions. Only 35% of these emissions are emitted within the EU. The largest single emitting country where emissions related to plastics consumed in the EU are emitted is China (18% of total GHG emissions). In recent years, the increasing quantities of plastic produced using coal-fired power plants resulted in an increase in the carbon footprint of plastics (Cabernard et al. 2022). This emphasizes the importance of decarbonizing global energy supply. Cabernard et al. (2022) show that total GHG emissions emitted by plastic products might decrease, if energy is provided using renewable sources. If such a decarbonization of the energy supply is not realized, emissions will increase substantially in the upcoming decades (Shen, Huang, et al. 2020). The EOL of plastic accounts for a substantial portion of their total life cycle GHG emissions (Figure 11). Recycling is by far the best option in comparison to incineration or landfilling. Presently, however, production is still the dominant source of GHG emissions related to plastic use (Figure 12). The total GHG emissions of the EU plastic value chain in 2018 amounted to 208.5 Mt CO_2-eq. This figure excludes plastic produced elsewhere (31% of plastics used in the EU are produced elsewhere, mainly China, see Figure 10), as well as plastic that results in a temporary carbon storage because of stock build-up and landfilling. In the latter two cases, CO_2 is most likely released at a later point in time.

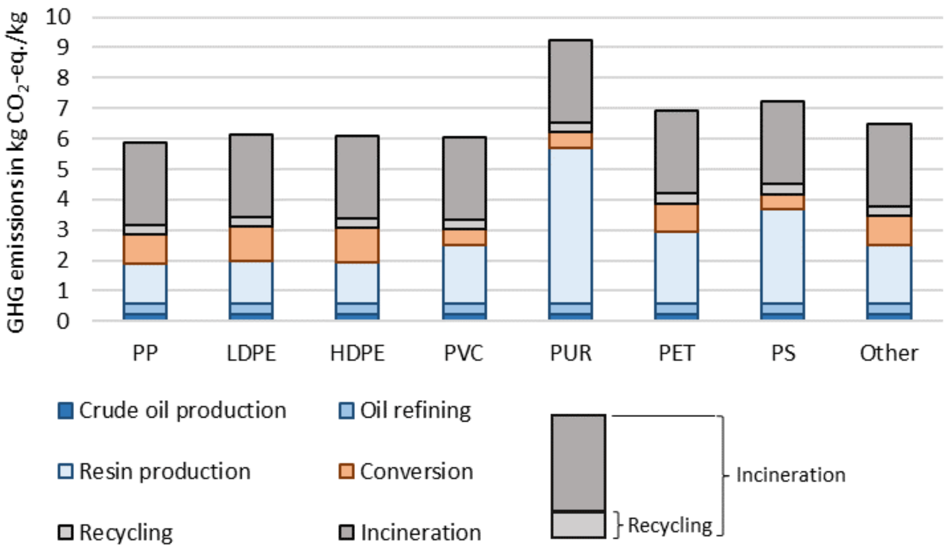


Figure 11 *GHG emissions of conventional plastic made from fossil mineral oil in the EU. Please note the depiction of the EOL: The light bar stands for GHG emissions if plastic is recycled. The dark gray bars (plain and patterned) need to be added to get the total emissions if the material is incinerated. If avoided emissions are considered, the total emissions are reduced by 0.98 kg CO_2-eq./kg (not depicted). Own depiction based on data provided in (Vanderreydt et al. 2021). Abbr.: EOL - end-of-life, PP - polypropylene, LDPE - light density polyethylene, HDPE - high density polyethylene, PVC - polyvinyl chloride, PUR - polyurethane, PET - polyethylene terephthalate, PS - polystyrene*.

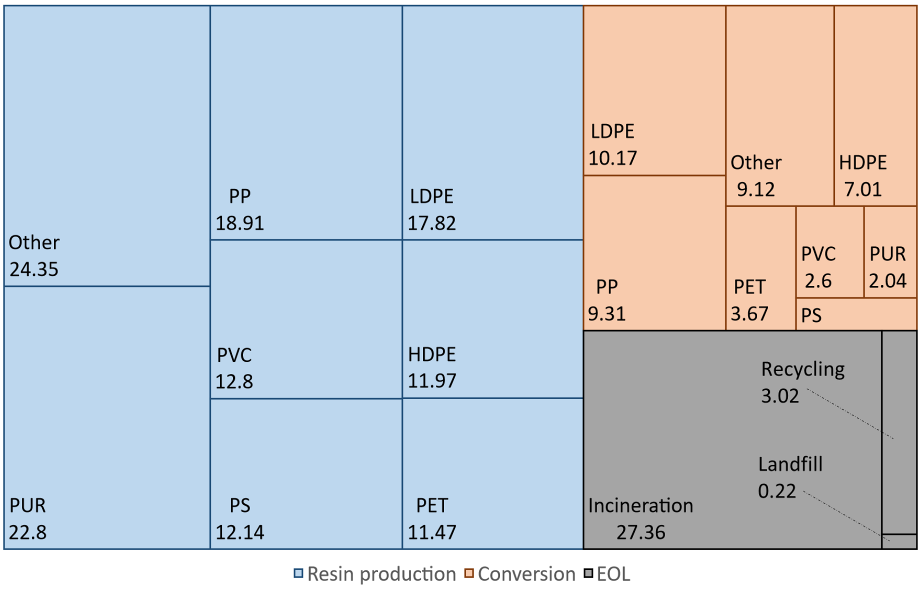


Figure 12 *Total GHG emissions of conventional plastic produced and used in the EU in Mt CO_2-eq. in 2018. Own depiction based on data provided in (Vanderreydt et al. 2021). Abbr.: EOL - end-of-life, PP - polypropylene, LDPE - light density polyethylene, HDPE - high density polyethylene, PVC - polyvinyl chloride, PUR - polyurethane, PET - polyethylene terephthalate, PS - polystyrene.*

The GHG emissions associated with bioplastics are lower than the GHG emissions emitted by conventional plastics (Figure 13). It should be noted that there is a much wider variability arising from the wide range of GHG emissions depending on the feedstock used, cultivation conditions and potential land-use change. Therefore, values should be considered as an indication of potential GHG emissions.

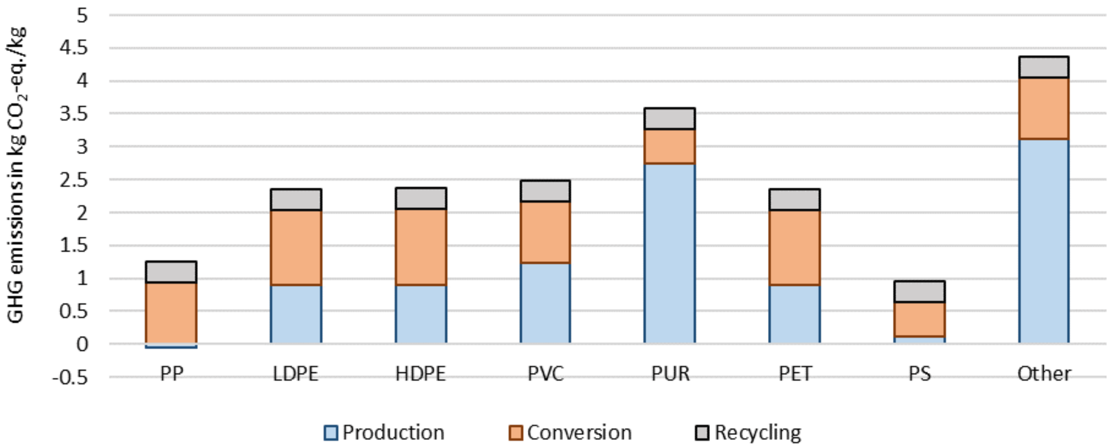


Figure 13 *GHG emissions of bioplastics according to corresponding fossil plastic Please note the depiction of the EOL: Composting and incineration of biobased plastics emit biogenic CO_2. This CO_2 was captured by the biomass. Therefore, these emissions are not depicted. Composting might also emit other GHG, such as CH_4 and N_2O. Analogously to conventional plastic (Figure 9), incineration of bioplastics results in the displacement of conventional energy generation: if avoided emissions are considered, the total emissions are reduced by 0.98 kg CO_2-eq./kg (not depicted). Own depiction based on data provided in (Vanderreydt et al. 2021). Abbr.: EOL - end-of-life, PP - polypropylene, LDPE - light density polyethylene, HDPE - high density polyethylene, PVC - polyvinyl chloride, PUR - polyurethane, PET - polyethylene terephthalate, PS - polystyrene.*

Figure 14 shows a range of GHG emissions and of resource use of conventional fossil-based plastics and bioplastics. The figure shows that bioplastics tende to be more sustainable in terms of GHG emissions and the use of fossil resources.

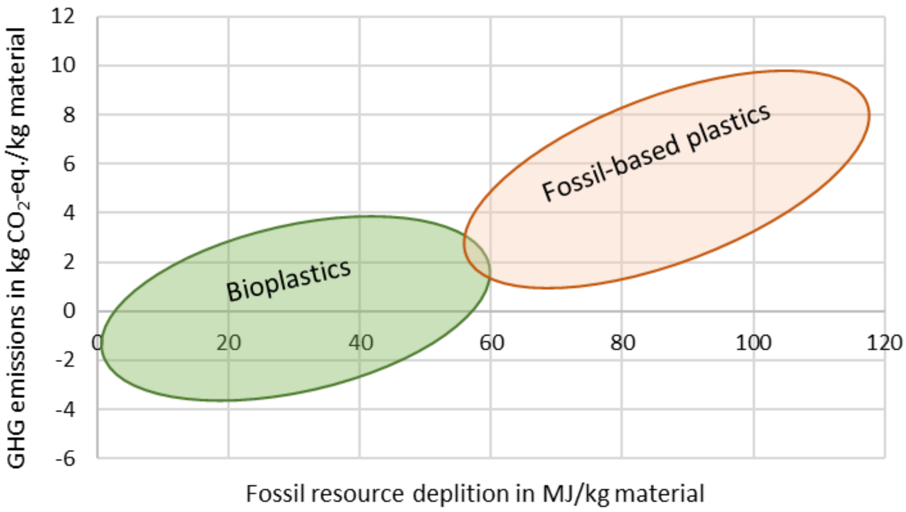


Figure 14 *GHG emissions and fossil resource (CED_f) use of conventional, fossil-based plastics and bioplastics. Own depiction adapted from (World Economic Forum, Ellen MacArthur Foundation, and McKinsey & Company 2016).*

3.2.3. Plastic pollution and its consequences

The leakage of plastics to the natural environment results in many negative impacts. The leakage of plastics mainly occurs in Asia, where 82% of plastic leakage is estimated to occur (World Economic Forum, Ellen MacArthur Foundation, and McKinsey & Company 2016). The United States and Europe are estimated to account for 2% of the total plastic leakages. All other countries account for the remaining 16% of plastic leakages. Plastic pollution poses an irreversible threat (MacLeod et al. 2021). Even under optimistic scenarios, emissions of plastics are expected to continue and increase. Once in the natural environment, the material is subject to degradation processes. The rate of degradation depends on intrinsic properties of the material (material type, additives, etc.), the environmental conditions (temperature, moisture, contact with other substances and molecules, etc.) as well as the extrinsic material properties (e.g. shape, particle size): estimates range from very short periods of time in case of biodegradable materials to millennia in case of larger solid objects, e.g. pipes made from HDPE or bottles made from PET (Chamas et al. 2020). Once in nature, plastic and plastic particles are subject to many different mechanisms, such as fragmentation, biofouling and oxidation, resulting in the release of smaller, more mobile and potentially more harmful substances.

The release of these substances results in organisms being exposed to potentially harmful substances. The plastic polymers used are made from polymers mixed with additives and processing aids. Examples of additives are antioxidants, biocides, fillers, flame retardants, impact modifiers, light stabilizers, nucleating agents, odor agents and plasticizers. A few examples of the most common processing aids are antistatic agents, blowing agents, catalysts, crosslinking agents, heat stabilizers, initiators, lubricants, solvents and viscosity modifiers. There are over 10,000 known substances contained in plastics used today of which more than 2,400 are of potential concern (Wiesinger, Wang, and Hellweg 2021). Of these ca. 53% are not subject to any management measure or regulation. About 4,100 substances lack a hazard classification. Hence, their level of concern is unknown. Organisms are exposed to these substances through direct contact, ingestion and inhalation. This exposure can happen through contact with the material containing the substances or through the leakage of the substances into the environment and a subsequent exposure to the substance or to its derivatives. Many of these are toxic, cancerogenous, mutagenic or endocrine disrupting and accumulate in organisms (bioaccumulation) (Wiesinger, Wang, and Hellweg 2021).

Aside from health effects arising from toxicity, plastic objects cause other harmful effects on species, e.g.

- Plastic particles change the turbidity of sea water resulting in changes in light transmission. Changes in light transmission can severely affect communities of phytoplankton, zooplankton and bacteria (Shen, Ye, et al. 2020). The complex global food web is thereby affected.
- Microplastic might seriously affect nutrient availability and oxygen content of seawater (Kvale et al. 2021; Seeley et al. 2020).
- Plastic changes soil properties affecting water holding capacity, nutrient availability and soil structure (Iqbal et al. 2020). This negatively affects soil organisms and plants, and eventually many other species of the complex global food web.
- Ingestion, exposure to harmful substances and entanglement results in severe negative impacts to species: a review paper summarizing the outcomes of 747 research studies identified 914 marine species that are affected by ingestion and/or entanglement (Kühn and van Franeker 2020). Many affected species are listed on the International Union for Conservation of Nature Red List (Gall and Thompson 2015). Yet, the effects of ingestion and exposure to plastic, its bioaccumulation, its transfer between organisms and trophic levels remain to be better understood (Provencher et al. 2019).

Recently, scientists have identified a potentially positive effect of plastics in the ocean: macro plastic debris may result in the formation of deep sea plastic biotas (Li and Sun 2022; Song et al. 2021). Micro and macro organisms colonize the particles and objects. After biofouling processes, plastic objects sink to the bottom of the ocean providing a vector for nutrients and for organisms to reach the deep sea. The sunken objects form patches with high concentrations of plastic debris.

4. Way forward: novel solutions are needed

The review in section 3 (part II) shows that the current plastics system is highly dysfunctional. Severe negative impacts threaten habitats, ecosystem services and species. At present, plastics are used in large quantities and existing waste collection and treatment systems are insufficient to prevent severe damage to nature. A fundamental change is needed.

A transformation towards a more sustainable packaging system comprises change in many ways:

- **More sustainable materials:** Bio-based plastics, plastics made from captured CO_2 and non-plastic alternatives (e.g. paper) can significantly reduce resource demand and GHG emissions. New solutions need to be brought to market maturity. This involves research activities in novel materials as well as upscaling and improvement of known alternatives. Certain alternative materials might bear the risk of specific negative environmental impacts (e.g. land-use change). Therefore, these alternatives need to be carefully assessed, e.g. with Life Cycle Assessments, in order to minimize negative externalities and to identify the most sustainable alternatives.

- **More sustainable production of conventional plastics**: The plastic industry is one of the biggest GHG emitters worldwide. Reducing the GHG intensity of energy supply can substantially reduce the negative impact of conventional plastic production in cases where no alternatives are available.

- **Sustainable EOL systems**: At the moment, only a minor share of plastics is kept in the economic system. The vast majority is either wasted (e.g. in landfills) or ends up in nature. The reasons for this are manifold: Lack of proper collection systems, littering and product designs making recycling impractical, just to name a few. Hence, change is urgently needed. This includes regulatory changes promoting proper waste management systems, measures to prevent littering and leakage of plastics to the environment as well as better product design. Careful product design comprises using minimal material input as well as improving the recyclability of products and local waste management systems but also increasing use cycles of packaging.

- **Reduction of packaging materials:** The demand for packaging materials (and plastics) is predicted to grow in the upcoming years. Better packaging design and more sustainable supply chains can help to reduce the overall quantity of packaging material needed.

- **Closing loops:** Ultimately, material loops need to be closed. This can be accomplished in two ways: closing the biological cycle or the technical cycle (Figure 15).

    - *Closing the biological cycle* requires the design of packaging materials and plastics in a way that they are fully biodegradable under natural conditions. All materials used should *fully degrade to harmless substances in short time-scales*. In such a system, materials degrade and leave nothing but nutrients and organic matter. Materials can be anaerobically digested, too. If this step is included, biomethane is produced and nutrients contained in digestate can be later returned to nature.

- *Closing the material cycle* requires a design of packaging materials and plastics, as well as an adequate EOL system allowing *full recyclability without any leakages to the environment*.

  If energy from renewable sources is used, both approaches can provide the most sustainable way of using plastics. The establishment of these two systems requires a holistic approach encompassing feedstock supply, material production, design, use and EOL. Which system is to be preferred depends on local conditions (e.g. existing EOL systems) and the specific use case (e.g. plastics prone to end up in the environment vs. plastics that are easily kept in the economic system).

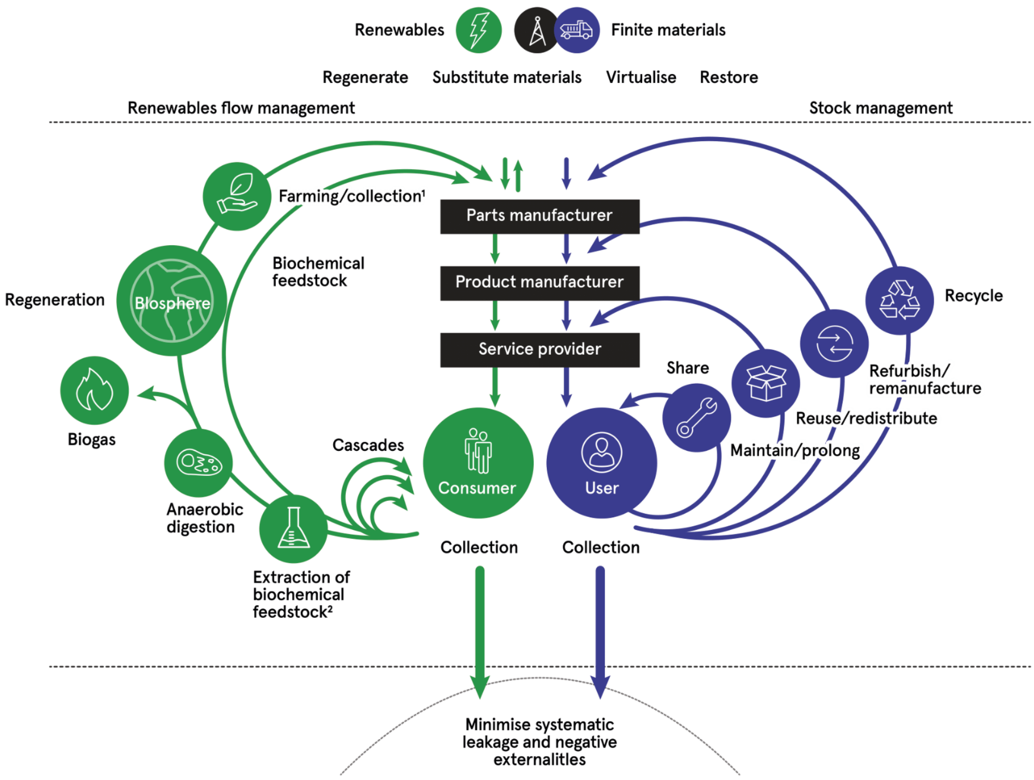


Figure 15 *Closing loops. A sustainable system closes the biological (green) or technical (blue) cycle. Own depiction, adapted from (World Economic Forum, Ellen MacArthur Foundation, and McKinsey & Company 2016).*

In order to improve these aspects, changes in policy and current economic practices are needed. More research needs to be done, research results need to be incorporated into business practices and a more sustainable behavior needs to become more attractive. All of this requires joint efforts of companies, researchers and policy makers. Actors bridging the gap between these actors are needed.

one.five fills this gap and offers a holistic approach to improve the existing dysfunctional system. one.five develops innovative packaging materials with their customers based on customer needs and sustainability considerations. The core of the business is to scale-up and improve promising packaging materials in order to reduce the demand for conventional, unsustainable materials. A key tool to identify the most promising alternatives are Life Cycle Assessments. one.five uses LCAs as a tool to assist and guide decisions on what type of material is the most preferable under eco-design principles and sustainability considerations. one.five designs packaging according to functional needs as well as the characteristics of the target market and, most importantly, takes existing EOL systems into consideration. In order to bring change for the better, such an approach is urgently needed.

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Annex

Table A.1 Used Ecoinvent 3.8 processes for the conventional PET sachet.

PET sachet	Processes
Production and raw material	● market for packaging film, low density polyethylene | packaging film, low density polyethylene | Consequential, U - GLO ● market for polyethylene terephthalate, granulate, bottle grade | polyethylene terephthalate, granulate, bottle grade | Consequential, S - GLO ● extrusion, plastic film | extrusion, plastic film | Consequential, U - RER
End of Life	● R1a-MSW: treatment of waste polyethylene terephthalate, municipal incineration | waste polyethylene terephthalate | Consequential, S - RoW ● R1b-LF: treatment of waste polyethylene terephthalate, sanitary landfill | waste polyethylene terephthalate | Consequential, S - RoW ● R2-100: treatment of waste polyethylene terephthalate, for recycling, unsorted, sorting | waste polyethylene terephthalate, for recycling, unsorted | Consequential, U - Europe without Switzerland ● R3-DE: 24.6 % recycling, 73.7 % MSW, 1.4 % landfill

Table A.2 Used Ecoinvent 3.8 processes for the one.five sachet.

one.five sachet	Processes
Production and raw material	● kraft paper production | kraft paper | Consequential, S - RER ● solvent production, organic | solvent, organic | Consequential, S - GLO ● market for tap water | tap water | Consequential, S - Europe without Switzerland ● market for electricity, medium voltage | electricity, medium voltage | Consequential, S - DE ● market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Consequential, S - Europe without Switzerland ● estimated one.five-layer - confidential (processes under development)
End of Life	● R1a-MSW: treatment of waste paperboard, municipal incineration | waste paperboard | Consequential, U - RoW ● R1b-LF: treatment of waste paperboard, sanitary landfill | waste paperboard | Consequential, S - RoW ● R2-100: treatment of waste paper to pulp, wet lap, totally chlorine free bleached | waste paper, unsorted | Consequential, U - RoW ● R3-DE: 24.6 % recycling, 73.7 % MSW, 1.4 % landfill

Table A.3 Images, graphics and icons used in Figure 8

PET	Left PET bottle	Icon made by freepix available from flaticon.
HDPE	Freeze bag	Icon made by freepix available from flaticon.
	Shampoo bottle	Icon made by freepix available from flaticon.
PVC	Cling wrap	Icon made by freepix available from flaticon.
	Cosmetic container	Icon made by freepix available from flaticon.
LDPE	Squeeze bottle	Icon made from justicon available from flaticon.
	Trash bag	Icon made from icongeek26 available from flaticon.
PP	Microwave dish	Icon made from itim2101 available from flaticon.
	Yoghurt cup	Icon made by freepix available from flaticon.
	Straws	Icon made by freepix available from flaticon.
PS	CD case	Icon made by Smashicon from flaticon.
	Cutlery	Icon made by freepix available from flaticon.
EPS	Styrofoam container	Icon made by Agung Rama available from laticon.
Other	Large gallon bottle	Icon made by freepix available from flaticon.

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