Increasing the quality and rate of Multi-layER packaging recycLINg waste

Baseline study of existing barriers and opportunities in the multi-layer plastic packaging value chain towards circularity

The MERLIN project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 101003883

Grant Agreement No:	101003883	Project Acronym:	MERLIN
Project Title:	Increasing the quality and rate of Multi-layER packaging recycLINg waste		
Funding scheme:	Horizon 2020 – Research & Innovation Action		
Project Coordinator:	ITENE – INSTITUTO TECNOLÓGICO DEL EMBALAJE, TRANSPORTE Y LOGÍSTICA		
WP Number:	6		
Deliverable number:	None		
Deliverable Title:	Baseline study		
Lead Beneficiary	9 – CSCP (Collaborating Centre on Sustainable Consumption and Production gGmbH)		
Start date of the project:	01.06.2021		
Duration of the project:	36 months		
Type of Deliverable	R (Document, Report)		
Dissemination level:	PU (Public)		
Authors:	Johannes Schön (CSCP), Ahmad ur Rehman Hafiz (CSCP), Fiona Woo (CSCP) & Jannik Giesen (CSCP)		
Contributors:	ITENE – Instituto Tecnologico Del Embalaje, Transporte Y Logistica IRIS – IRIS Technology Solutions S.L. ROVIMATICA – ROVIMATICA S.L. CESPA – CESPA S.A. UNIBO – Alma Mater Studiorum Universita Di Bologna IONIQA - Ioniqa Technologies B.V INDORAMA – Indorama Ventures Europe B.V. CEA – Commissariat À l'Énergie Atomique Et Aux Ènergies Alternatives PARTICULA – Particula Group d.o.o		

	ITC – ITC Packaging, S.L.U ICIMENDUE – ICIMENDUE SRL ENCO – ENCO SRL EuPC – European Plastics Converters
Acknowledgement	Special thanks to: Mario Mensitieri (ICIMENDUE), Ashwin Briedjlal (INDORAMA/IVL), Willem Christiaans (INDORAMA/IVL), Jesper van Berkel (INDORAMA/IVL), Jose Luis Dieguez Garcia (ITENE), Nerea Abad Fernandez (ITENE), and Miguel Angel Gomez (ITENE)
Version:	**0.1**

Grant Agreement No.: 101003883

Table of Contents

Executive Summary 6

About the study 7

1. INTRODUCTION 9

2. MULTI-LAYER PLASTIC PACKAGING 12

   i. PROPERTIES AND CHARACTERISTICS 12

   ii. FACTS AND FIGURES ABOUT THE RECYCLING OF PLASTIC PACKAGING IN THE EU 14

   iii. RECYCLING TECHNOLOGIES AND PROCESSES 19

3. BASELINE STUDY 20

   i. VALUE CHAIN 20

   ii. STAKEHOLDERS 21

   iii. MOTIVATIONS, OPPORTUNITIES AND BARRIERS 22

   iv. CONCLUSION 31

4. OUTLOOK 32

References 35

Index of Tables

Table 1: Plastic in use for packaging, properties and use case examples 13

Table 2: Quantities of flexible plastic-based multi-layer packaging in five categories in Europe 16

Table 3: Treatment of packaging waste in Germany in 2015 18

Table 4: Overview of chemical recycling processes 20

Table 5: Stakeholder clusters of multi-layer plastic packaging 22

Index of Figures

Figure 1: Various layers of multi-layer packaging 13

Figure 2: Packaging waste generated and recycled in 2019 (kg per capita) 15

Figure 3: Packaging waste generated by packaging material, EU, 2019 (in %) 15

Figure 4: Packaging waste generated, recovered and recycled, EU, 2009-2019 (kg per capita) 16

Figure 5: European plastic packaging waste management in 2015/2016 18

Figure 6: Plastic packaging value chain and its recycling routes, including existing and emergent technologies 19

Figure 7: Multi-layer packaging value chain developed in MERLIN 20

Executive Summary

This baseline study gives an overview of the scope, challenges, status quo and driving factors of efforts to increase circularity in multi-layer plastic packaging. Most importantly, it identifies the motivations, opportunities and barriers that major stakeholders face along the multi-layer plastic packaging value chain that enable them to or prevent them from contributing more to circular value chain. These factors are crucial for achieving significant change and therefore building a baseline for all MERLIN project activities and the monitoring of their results. By enabling stakeholders to exploit opportunities, mitigate barriers and affect unfavourable framework conditions, the MERLIN consortium partners will lead the change towards circularity in multi-layer plastic packaging.

With a yearly volume of about 3.03 million tonnes, which is about 17% of all plastic packaging in the EU, multi-layer plastic packaging waste is a significant part of the current waste stream. Due to its complex structure and often heterogeneous composition, recycling of multi-layer plastic packaging remains a major challenge. This leads to currently very high rates of incineration for energy recovery and landfilling compared to only marginal rates of recycling. An increase in circularity would reduce environmental impact, decrease dependence on raw materials from fossil sources and potentially make a significant contribution towards reaching the EU´s packaging waste recycling rate target for 2030, which is 80 %.

The analysis of motivations, opportunities and barriers of the core stakeholders towards increasing circularity gives a comprehensive overview of what drives or hinders the necessary change. Those stakeholders seeking innovation in the areas of sorting, delamination, material reconstruction and waste collection are mostly driven by economic and environmental incentives. The prospect of tapping into new revenue sources from existing waste streams and at the same time significantly reducing environmental effects serves as a strong stimulus to research new approaches. The challenges these stakeholders face mostly revolve around technological and regulatory issues. The application of new technologies and processes is key to developing effective, resource-efficient and scalable procedures for the valorisation of multi-layer plastic packaging waste. In addition, regulatory changes may be required to support and enhance the introduction of these new procedures as well as incentivise the waste and recycling industries to take them up.

Stakeholders aiming to facilitate acceptance, utilisation and promotion of the resulting materials and products of recycled multi-layer packaging react to the pull factor of an increasing demand for more sustainable products by end consumers. By providing more sustainable packaging, companies and consumers build up their image of acting in a "greener" way while retaining their market shares or standard of living, respectively. The barriers are mainly technical, such as ensuring compliance with legal requirements on food safety and matching consumer expectations on product properties and appearance as well as keeping potential price increases to a minimum.

Addressing and exploiting these opportunities and barriers will require close collaboration of different stakeholders across the value chain and active engagement of all relevant stakeholder groups throughout and beyond the project duration. Only with broad support of the industrial and scientific society can the technological, social, political and behavioural changes necessary to increase circularity in the multi-layer plastic packaging industry be attained.

About the study

This study presents a current baseline for multi-layer packaging waste in Europe. It defines the value chain of multi-layer packaging and all the stakeholders involved. Based on this study, it assesses existing motivations, barriers and opportunities of key stakeholders in increasing recycling of multi-layer plastic packaging. When looking ahead, the status quo defined in this study represents the basis for recommendations and development of new sustainable solutions in the multi-layer packaging sector.

This study is to be seen in context to the stakeholder engagement plan deliverable of the MERLIN project. MERLIN is a 36-month research project aiming to provide innovative systemic solutions for the processes required to increase the quality and rate of recycled multi-layer packaging waste. MERLIN is led by a consortium consisting of actors along the multi-layer plastic packaging supply chain. This involves the steps from producer to final consumer, and from research to policy makers. It is the project's aim to develop and promote innovative processes for sorting, delaminating and recycling of rigid and flexible multi-layer plastic packaging waste from post-consumer and post-industrial sources to obtain new high-performance packaging solutions for the food packaging industry.

Study content & intended audience

This study gives you a brief introduction of the design and recycling challenges of multi-layer plastic packaging. In the main part, we introduce you to the complete value chain and a cluster of the most relevant stakeholders to the life-cycle of multi-layer plastic packaging. We then present you the opportunities, barriers and motivations within the sector towards more sustainable packaging in the industry, e.g. which food regulation hinders the re-use of plastic packaging, or what technologies can enable higher recycling rates?

Followingly, the study concludes with a baseline statement and gives outlook on the challenges, and research and innovation projects ahead.

The intended audience for this baseline study comprises many stakeholders. It firstly includes the partners of the MERLIN project consortium. In addition, it is addresses waste management companies, municipalities, raw material producers, sorting facilities, sorting technology providers, manufacturers and plastics converters. Downstream, it also addresses retailers, packaging brand owners, private and commercial end-consumers. On a policy level, this study is aimed at national and international legislators, policymakers, standardisation bodies and researchers as well as civil society organisations working on related topics.

Scope

This study aims to define the status quo for the management of multi-layer plastic packaging for the geographical scope of the European Union. Given the constellation of the project consortium, the views, facts and figures may increasingly apply to the waste and packaging sectors of Spain, Italy, the Netherlands, France, Croatia, Belgium and Germany.

This study does not include an overview or a comparison of the different waste management systems, multi-layer plastic packaging resource streams, or recycling technologies. Nonetheless, the study provides valuable insight into the sector itself and thus there is a relative share of transferability to other European countries. This baseline study focuses on plastic packaging, specifically multi-layer plastic packaging in flexible and rigid form.

Grant Agreement No.: 101003883

Why should you read this study?

After reading this study, you gained an overview over current data on plastic packaging & multi-layer plastic packaging waste, innovative collection, sorting and recycling technologies. Given the opportunities and barriers of the sector, you develop understanding on leverage points to improve recycling and enabling the circular economy in the plastics sector. Further, you gain an overview about the goals and action & innovation research of the MERLIN consortium.

1. INTRODUCTION

Plastic packaging has been celebrated as an innovative, light and safe way to package valuable goods in every sector of modern production and consumption. At the same time, it has been criticised for its harm to the environment due to its durability and persistence in water bodies and sensitive ecosystems.

The European Commission adopted the EU plastics strategy in 2018 that integrates into the ongoing Circular Economy ambitions since 2015. The strategy's goal is to protect and reduce marine litter, greenhouse gas emissions and the European dependence on imported fossil fuels. The political ambition is to support more sustainable and safer plastic consumption and production patterns. This ambition translates into finding pathways to transform the way that plastic products are designed, produced, used and recycled within the European Union. In order to reach the goals set in the strategy, the European Commission is driving innovation and investment to scale up the development of smarter and more recyclable plastic materials, more efficient recycling processes and to trace and remove harmful substances. The MERLIN project (www.merlinproject.eu) is aligned with the European plastics strategy to ensure that by 2030 all plastic packaging is designed to be recyclable or reusable, aiming towards decreasing the quantity of waste generated (European Commission, n.d.).

Background and problem statement

Multi-layer plastic packaging is a common application in the fast-moving consumer goods sector and combines functionalities of several material layers. It increases product protection and prolongs shelf-life of packaged food and other perishable goods. The packaging is lightweight and is diverse in application, e.g. sealed bags or pouches. It provides surface area for communicating product information to consumers, e.g. ingredient lists, nutritional values, expiry date, portion size and other information such as branding and manufacturing details.

Nevertheless, it represents a challenge for existing recycling systems. The multiple layers are usually compounded in such a way that it requires additional sorting and delamination technologies and processes to identify and recycle the material in conventional waste streams. The advantages of the packaging technology, i.e. enabling minimal material thickness when combining layers, allowing for barriers, sturdiness, mechanical strength, and heat tolerance, led to a diversity of packaging goods, but also resulted in a heterogeneity in the composition of waste material. Plastic packaging material has a short use phase, large production volume and various compositions, which creates challenges for an effective and environmentally beneficial waste management (Soares et al., 2022). These characteristics make efficient and targeted recycling for high-quality recycled material very difficult.

The demanding buyers, especially the food industry, have very high performance requirements for packaging. About 17 % of the total circulating plastic packaging belongs to the category of multi-layer plastic packaging. This equals to an amount of 3.03 Mt of packaging. The food sector also creates the most demand, accounting for 87 % of European flexible multi-layer plastic packaging composites (Bavarian Research Alliance, 2021).

Although there are a few recycling solutions to recycle multi-layer plastic packaging, the available technologies are limited to specific polymer types. For the type of packaging under study, there has not been successful recycling of post-consumer waste yet. The variety of materials used, e.g. PP, PET, HDPE, aluminium and paper, and the adhesive compounding of the layers make conventional recycling difficult. This type of waste usually contaminates the recycling material stream and thus much material intended for recycling is rejected. Currently in the given waste management regime, multi-layer plastic packaging is incinerated or landfilled and thus is misaligned with the waste hierarchy imposed by the European Waste Framework Directive (Kaiser et al., 2017).

The European Commission plans for all plastic packaging to be reusable or recyclable in the future. EU legislation will impose a ban on all non-recyclable plastic packaging from the European market from 2030 (Bauer et al., 2021). The EU´s packaging waste recycling rate target for 2030 is 80 % (European Commission, 2014).

The identified gap between missing infrastructure and recycling difficulties of multi-layer plastic packaging must be closed. Therefore, many countries in the EU will have to invest in new technologies and systems of collection, sorting and recycling.

It is due to the increasing environmental regulation, missing recycling infrastructure for multi-layer plastic packaging, and expected growth of plastic packaging circulation that innovative solutions have to be found and developed.

Many innovative solutions lie within the paradigms and ideas of the Circular Economy. This concept has been popularized and is in use by the European Commission since 2015 with the Circular Economy Action Plan. This concept can provide us and our stakeholders with both a solution to the plastic packaging issue, but also with welfare growth. The current design and use of plastic packaging waste presents an environmental and economic opportunity for closing material loops. By embedding circular economy principles (see box below) at the design, use and end-of-use phases, material life-time can be significantly extended which not only reduces needs for virgin raw materials but also lowers amounts of waste and environmental pollution (Ellen MacArthur Foundation, 2014).

Circular Economy Definition

A circular economy aims to redefine growth, focusing on positive society-wide benefits. It entails gradually decoupling economic activity from the consumption of finite resources, and designing waste out of the economic system.

Underpinned by a transition to renewable energy sources, the circular model rebuilds economic, natural, and social capital. It is based on three principles:

- Design out waste and pollution
- Keep products and materials in use
- Regenerate natural systems

More at: https://www.ellenmacarthurfoundation.org/circular-economy/concept

To achieve more sustainable development in the plastic packaging sector it requires the transformation of a linear plastic industry into a circular economy for plastics. The linear system shown before needs to close the material loop and maintain the value and reduce the carbon footprint of the plastic packaging products (see figure below).

In general, the opportunities and benefits of transforming today's economy into a circular one lie in three spheres. Like mentioned before, a circular plastics industry brings opportunity to increase employment and economic growth while creating technological and research innovation within the field of plastic packaging.

Ecologically, the benefits of multi-layer plastic packaging recycling lie in GHG emission reductions, reducing resource consumption and avoiding environmental damage due to landfilling or littering. Lastly, citizen and consumers would benefit from safer products and services, more sophisticated consumer rights e.g. right to repair, and greater utility in products and services (Ellen MacArthur Foundation, 2014).

Methodology

This baseline study is the result of close collaboration between the consortium partners and the ongoing project work of MERLIN. It aims to define the status quo for the management of multi-layer plastic packaging with the geographical scope of the European Union. Given the constellation of the project consortium, the views, facts and figures may particularly apply to the countries of Spain, Italy, the Netherlands, France, Croatia, Belgium and Germany.

The methodological approach of the study involved desk research, surveys, and focus groups and individual interviews with experts from the MERLIN project. Both insights and hypotheses of the research have been validated and reviewed by the MERLIN consortium partners.

Desk research was carried out to analyse academic articles and grey literature addressing the topic of plastic waste, recycling and treatment as well as material revalorisation and innovation favouring circular economy objectives.

The purpose of the survey was to build a holistic view of the multi-layer packaging plastic waste value chain and its key stakeholders. It aimed to gain a better understand the different perspectives, intentions and challenges stakeholders face. Focus groups were used to validate and qualify survey results as well as fill in blind spots.

2. MULTI-LAYER PLASTIC PACKAGING

i. PROPERTIES AND CHARACTERISTICS

Multi-layer packaging is produced to combine functionalities of distinct materials such as polymers, paper, aluminium, and organic or inorganic coatings. These materials are combined to provide many functions, including food safety, strength (to protect from abrasion), hygiene and sealing. Other functionalities of multi-layer plastic packaging are barriers against moisture, oxygen, light, odour, flavour or chemicals. Two types of multi-layer plastic packaging are commonly used for food packaging: flexible packaging like pouches, bags and lidding, and rigid packaging like trays, cups, and bottles.

Multi-layer packaging accounts for 26 % of the flexible packaging market by weight (Soares et al., 2022). In general, most existing multi-layer packaging consists of three to twelve layers, but in the case of food packaging, it usually consists of three to seven layers (Butler & Morris, 2016).

The table below provides an overview of the various materials in multi-layer packaging and their specific uses and functionalities:

Packaging material	Background	Beneficial properties	Example of uses
Polyethylene (PE)	• Can be used as high-density polyethylene (HDPE), low-density polyethylene (LDPE), or linier low-density polyethylene (LLDPE) • PE as the most commonly used type of plastics	• Barrier against moisture, oxygen • Can be used as sealant, tie resin adhesive and structural layer • Combination with gas/aroma barriers (e.g., PA, EVOH)	• Beverage cartons (usually contains LDPE layer)
Polypropylene (PP)	• Thermoplastic polymer • Is frequently combined with PE • Metallisation is common for dry food products	• Slightly harder than PE and more heat resistant • High oxygen barriers • Coated with heat seal coatings (PVDC, acrylate) for mechanical strength	• Dry food products • Flip-top bottles • Microwavable packaging
Polyamide (PA)	• A polymer with repeating units linked by amide bonds • Polymer combinations of PA with PE is common	• Oxygen as well as oil, grease, and aroma barrier • Mechanical strength • Heat-sealable	• Vacuum packaging • Meat packaging • Thermoformed food packaging
Polyethylen terephthalate (PET)	• A thermoplastic, used for production of synthetic fibre and bottles • PET accounts for about 30 % of global demand of bottle production	• Oil and grease resistance • Use of PET is attractive for its printability, thermal, mechanical as well as optical properties	• Soft drinks • Food packaging such as bottles, meat, or cheese
Ethylene vinyl alcohol (EVOH) **Ethylene Vinyl Acetate (EVA)**	• Given its strong barrier against oxygen and gas, EVOH´s use in packaging structures extends the shelf life of food products	• Barrier against oxygen, oil, and grease • Highly transparent • Weather resistant • Oil and solvent resistant • Flexible, mouldable, recyclable, and printable	• Snack products

Packaging material	Background	Beneficial properties	Example of uses
Polyvinylidene dichloride (PVDC)	• A homopolymer of vinylidene chloride • Used in mono- or multi-layer variations	• Barrier properties against oxygen and moisture • Abrasion protection	• Shrink films or stretch wraps
Coatings such as aluminium oxide (AlOx) and silicon oxide (SiOx)	• Can be used between layers to enhance the durability • Can be combined with PET in multi-layer flexible packaging	• Barrier properties against oxygen and moisture • Offers transparency at thicknesses in the nanometre range	• Ready-to use meal
Paper	• Combinations include with PE, EVOH and foil	• Increases rigidity/stiffness of multi-layer packaging	• Ready-to use meal

Table 1: Plastic in use for packaging, properties and use case examples
Based on: European Commission. Joint Research Centre., 2016; Kaiser et al., 2017; Lamberti et al., 2020; Reichert et al., 2020; Soares et al., 2022

Various polymers are applied, such as polyolefins PE and PP and chemical variants (HDPE, LDPE, LLDPE), or polyesters such as PET. Apart from the number of layers, based on the degree of flexibility, multi-layer packaging can be categorised as flexible packaging (such as films) and rigid packaging (such as beverage cartons and multi-layer bottles) (Ramos et al., 2015). Besides other specific barrier effects, the inner and outer layers of packaging have additional functions.

The inner layer comes in direct contact with the food material, so it is important that the material must be inert and not react with any food constituents. The inner layer should also have good sealing ability at lower temperatures. The outer layer must offer mechanical stability and printability as well as barrier functions (Butler & Morris, 2016).

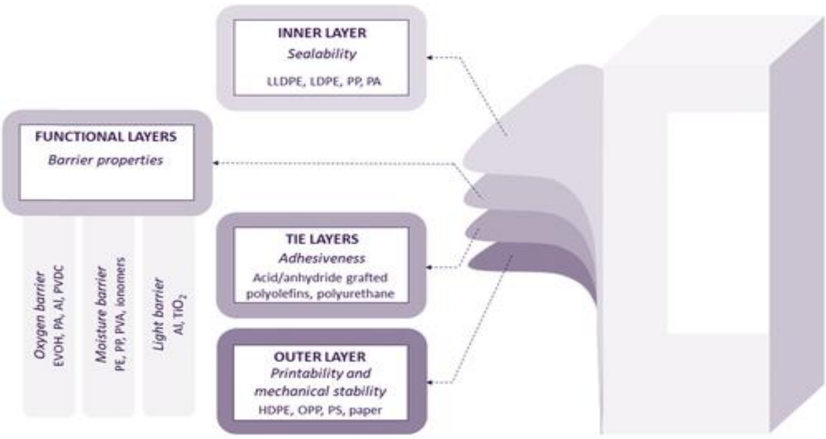


Figure 1: Various layers of multi-layer packaging
Based on: Butler & Morris, 2016; Ebnesajjad & Khaladkar, 2018; ILSI Europe, 2011

Advantages and disadvantages of multi-layer plastic packaging use

The advantages of multi-layer plastic packaging are many and diverse. By combining suitable properties of different materials, e.g. oxygen barrier or water barrier, the use of multiple layers significantly increases the shelf life of products. Multiple layers also provide multiple functionalities, e.g. contamination protection, light barriers, light weight, label printing, and consumer communication and branding. Another advantage of this packaging type is its durability and resistance to external forces, which keeps the protected good intact. Lastly, the production costs of plastic packaging is relatively low and thus multi-layer plastic packaging is a cost-efficient way of protecting and transporting goods.

When packaging goods, high durability is a major advantage. However, when managing waste and considering the environment, durability becomes an issue. Plastic does not degrade and harms open ecosystems, endangers wildlife, and causes pollution. Furthermore, due to abrasion, there is also the issue of micro-plastic that ends up in the human and animal food network.

Additionally, plastics are made from hydrocarbons and fossil fuels that are linked to the entire value chain of fossil fuels, including exploration, drilling, transportation and distribution of oil and gas. This value chain means plastics are implicated in high environmental risk and are not sustainable due to its indirect connection with the greenhouse gas effect and climate change.

ii. FACTS AND FIGURES ABOUT THE RECYCLING OF PLASTIC PACKAGING IN THE EU

The experience of our research has shown that the data availability and data quality on multi-layer plastic packaging and its waste is relatively low. Recent studies from Material Economics confirm this thesis and state that Europe generates about 45 million tonnes of plastic waste per year which is 50 % more than the 25-30 million tonnes assumed by policy-makers and the plastics industry. The think tank estimates that only 15 % of end-of-life plastics generated each year are recycled into new materials (Material Economics, 2022).

Agora Industry has similar perceptions about data on plastics recycling: "Statistics on plastics recycling are incomplete and unreliable" (Sartor et al., 2022). This information partly coincides with the information provided by our stakeholders. Therefore, the following data and facts in this chapter should be viewed with caution and critically scrutinised. Nevertheless, they are meaningful and roughly define the field for the recycling of multi-layer plastic packaging.

This chapter presents figures that relate to the global and European situation. Some of these relate to packaging in general as well as plastic packaging and multi-layer plastic packaging.

The Ellen MacArthur Foundation (EMF), in collaboration with the World Economic Forum and McKinsey & Company, released a report on the global linear plastic system in 2016. In the past 50 years, the amount of plastic has increased by a factor of 20. The report assessed the global material flow of plastic:

- From an annual production of 78 million tonnes, 98 % is produced from virgin feedstock
- End-of-life plastic packaging goes to recycling streams, energy recovery by incineration, landfilling, and leakage
- A whopping 32 % of plastic packaging materials in 2013 was lost and is considered leakage. Furthermore, 40 % of this material ends up in landfills, while 14 % is incinerated
- 14 % of the 78 million tonnes of the global annual production of plastic packaging is collected for recycling. 8 % of this feedstock is downcycled while 4 % of the material is lost due to process losses. Only 2 % of the total feedstock circulates in a closed loop.

The study shows that the plastic industry and plastic consumption and production are designed in a linear way. Most of the used plastics end up in landfills or in the open environment and pollute marine and land ecosystems (WEF et al., 2016).

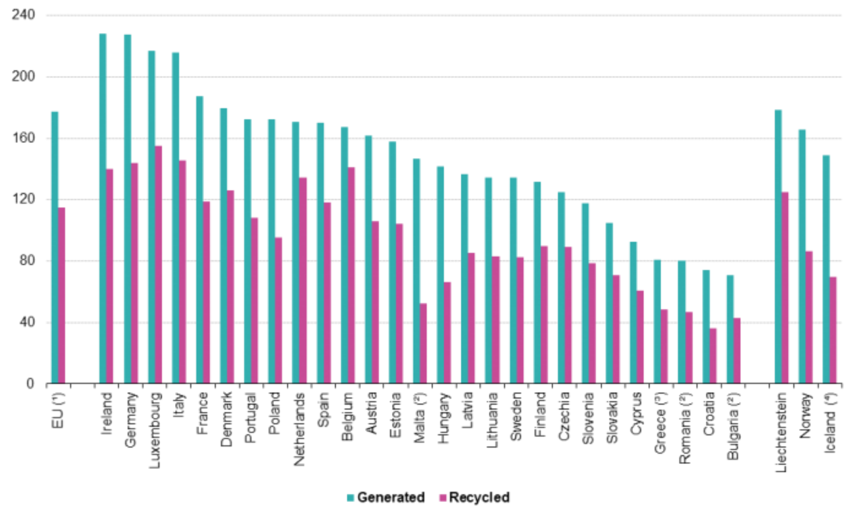


Figure 2: Packaging waste generated and recycled in 2019 (kg per capita)
Source: eurostat, 2021

In 2019, the annual packaging waste per capita in the EU was estimated at about 177 kg (eurostat, 2021). This packaging waste includes all packaging material. At a country level (per capita) the waste generation of plastic packaging ranges from 74 kg in Croatia to 228 kg in Ireland. Considering the MERLIN consortium partner countries, Germany, Italy and France rank second, fourth and fifth respectively in Europe. The Netherlands, Spain and Belgium rank nineth, tenth and eleventh at around 170 kg packaging waste generated per capita (see figure 2).

In figure 2, you can see that the most common types of packaging waste in the EU in 2019 were paper and cardboard (41 %), plastic (19 %), glass (19 %), wood (16 %) and metal (5 %).

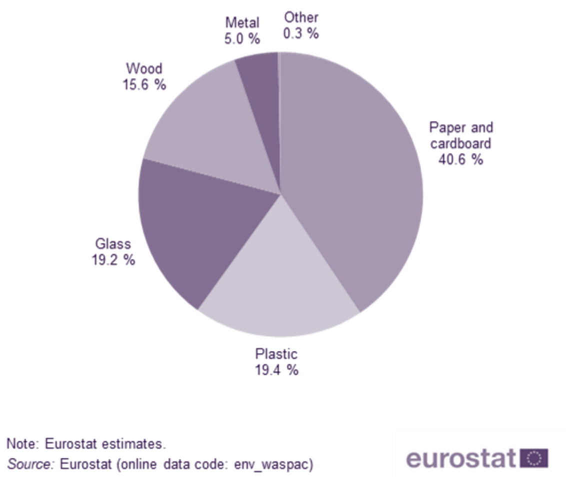


Figure 3: Packaging waste generated by packaging material, EU, 2019 (in %)

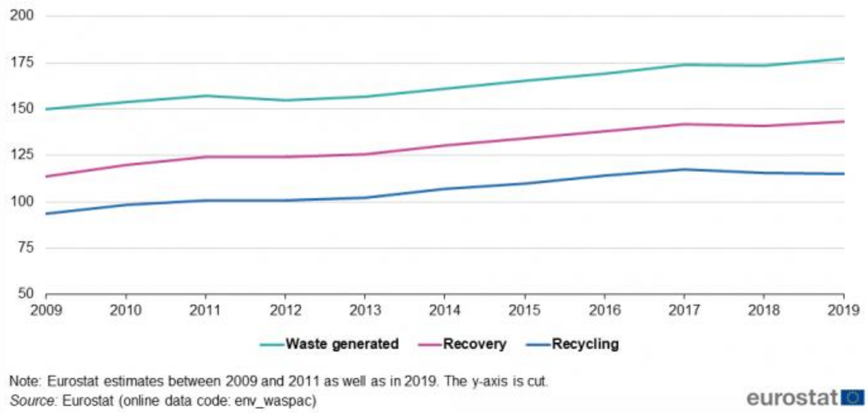


Figure 4: Packaging waste generated, recovered and recycled, EU, 2009-2019 (kg per capita)

In the EU, the recycling rate of packaging waste went up from about 63 % in 2009 to 65 % in 2019. The recycling rate and the recovery rate evolved in parallel. The recovery rate including incineration rose from 76 % in 2009 to 81 % in 2019 (eurostat, 2021).

Figure 4 shows the evolution of the volume of packaging waste generated, recovered and recycled per inhabitant. In comparison to the previous year, the amount generated in 2019 increased by more than 2 %. The amount recycled increased by 1.5 %. However, the amount recovered decreased slightly, by 0.3 %. Between 2009 and 2019, the amount generated increased substantially, by more than 18 %. Recycling and recovery volumes increased even more over the same period, by about 23 % and 26 %, respectively. Plastic packaging is also the type of packaging with the lowest recycling rate in the EU (approx. 42 %) compared to other materials. The share of plastic waste recovered or recycled varies amongst EU member states (Wecker, 2018).

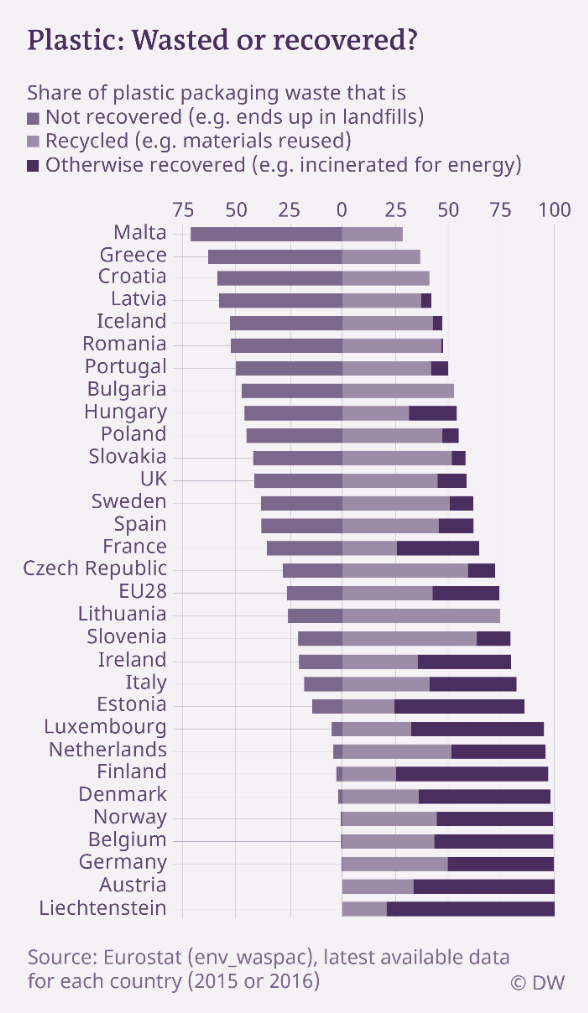
Category	Materials	Mio. m² film	Share in m²-%
Simple multi-layers	Total Thereof: PA/polyolefin	**6565.6** 2710.2	**37.1** 15.3
Packaging with organic barriers	Total Thereof: EVOH	**4499.9** 4304.7	**25.4** 24.3
Thermoformed packaging	Total Thereof: PA/polyolefin	**2482.1** 756.3	**14.0** 4.27
Packaging with inorganic barriers	Total Thereof: PET-BO/layer/polyolefin	**2996.1** 1362.9	**16.0** 7.7
Packaging with Al-foil	Total Thereof: PET/Al/Plastic	**1153.1** 829.1	**6.5** 4.7
Total		**17696.9**	**100**

Table 2: Quantities of flexible plastic-based multi-layer packaging in five categories in Europe
Based on: Kaiser et al. (2017) for the year 2016

The German Association of Packaging Market Research (GVM) divides multi-layer packaging into five categories. Based on estimations of the GVM, Kaiser et al. (2017) calculate and approximate the absolute and relative amount of multi-layer plastic packaging waste in Europe in table 2. The five categories are i) flexible plastic composites without a barrier layer ("simple multi-layer"), ii) flexible plastic and plastic composites with an organic barrier layer, iii) flexible metallised plastic and plastic composite films with coatings from AlOx or SiOx respectively, iv) thermoformed plastic and plastic composites, and v) plastic and plastic composites with aluminium foil.

This categorisation only reflects multi-layered packaging with a polymer content higher than 50 % and paper-free packaging only. The figures in table 1 are an estimate of European figures based on extrapolation of data on Germany. These are likely to have shortcomings in absolute numbers and relative share, but are sufficient to give an estimation of the quantities of multi-layered plastic packaging for the baseline study.

For multi-layer plastic packaging there are generally three processes in play. Firstly, there is energetic utilisation and recovery by waste incineration. Secondly, multi-layer plastic packaging can be mechanically recycled (polymer chains stay intact; use of shredding, solving or melting) and thirdly, there is chemical recycling (polymer components are broken down and turned back into oil/hydrocarbon components). In the example of Germany, we see that only a marginal amount of multi-layered plastic packaging is recycled chemically or mechanically (see table 3 below).



There is a high degree of heterogeneity when it comes to the various forms of waste treatment across Europe (see figure 5). Considering that the EU Commission has high ambitions for the circular economy especially in the plastics sector, the level of material reuse is rather low. Noteworthy is that there are nine EU members that have recycling or recovery streams and thus manage almost 100 % without landfilling. On the other hand, landfilling is still a common practice in the EU. The EU Landfill Directive is setting targets to phase out landfilling practices, e.g. by 2030, restrictions on landfilling of all waste that is suitable for recycling or other material or energy recovery, are introduced.

Further, countries such as Lithuania, Slovenia or Czechia have relatively advanced recycling practices that are beyond average.

The practical implementation of the EU Waste Framework Directive and its waste hierarchy from preferred waste management practices, e.g. reduction and reutilization and less preferred practices e.g. recycling, recovery and landfilling, needs stronger enforcement.

Figure 5: European plastic packaging waste management in 2015/2016
Based on: (Wecker, 2018), Copyright by DW

Recovery				Removal in kt/%		
Total	Mechanical	Chemical	Energetic	Total	Disposal	Incineration without energy recovery
2867 kt 100 %	1130 kt 39.4 %	50 kt 1.7 %	1678 kt 58.8 %	3 kt 0.1 %	3 kt 0.1 %	0 kt 0.0 %

Table 3: Treatment of packaging waste in Germany in 2015
Based on: Kaiser et al., 2017 by PlasticsEurope, 2016

The plastics and plastic packaging sector is confronted with difficult challenges given the new policy targets and regulative frameworks for the recyclability of multi-layer plastic packaging. Taking waste management in Germany as an example (table 3), there is a gap between the current state of recycling and the ambitions of the EU plastics strategy. The next chapter gives a brief overview of recycling technologies and processes to overcome that gap and to make a more sustainable multi-layer plastic packaging industry possible.

iii. RECYCLING TECHNOLOGIES AND PROCESSES

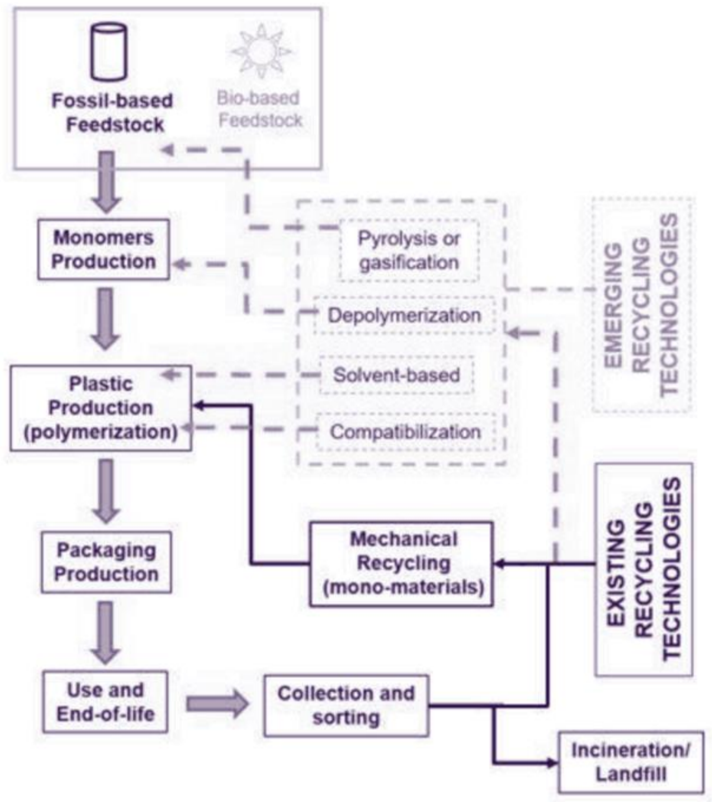


Figure 6: Plastic packaging value chain and its recycling routes, including existing and emergent technologies
Source: Soares et al. (2022)

As depicted in Figure 6 below, mechanical recycling is the usual way to recycle packaging. It includes grinding, shredding and washing. The efficiency of mechanical recycling varies from plastic to plastic, averaging at an estimated 60 %. It is difficult to recycle multi-layer packaging because of the need to separate and delaminate the different layers (e.g. aluminium from its polymer content). Furthermore, heterogeneity in multi-layer plastic packaging makes it even harder to recycle (Walker et al., 2020).

Chemical recycling technologies such as solvent-based techniques and pyrolysis (represented by dashed lines arrows in Figure 6) are emerging as demand for alternative recycling techniques that can process advanced packaging complexities such as multi-layer plastic packaging increases. The following table provides an overview of the chemical recycling processes:

Technology	Description
Delamination	• Separation of layers through bonding damage • Different technologies are emerging (e.g., a German company developed a technology which delaminates layers and includes a shredding step followed by a microemulsion with a surfactant that promotes layers' separation
Selective-dissolution	• Dissolving polymers using solvent • Taking the advantage of polymers' different solubility, in this process, a specific solvent, dissolves the target polymer, and other polymers remain at a solid phase; then, the solvent is used to target another polymer, or a different solvent can be used
Compatibilization	• Compatibilization uses chemical substances to increase multi-layers' mechanical stability (multi-material multi-layers include polymer blends which are unstable) and further recycle all layers in a single stream without separation
Feedstock recycling	• Processes known to perform this are gasification, pyrolysis, fluid-catalysed cracking, and hydrocracking

Table 4: Overview of chemical recycling processes

Based on: Soares et al. (2022)

3. BASELINE STUDY

The core of this study is a baseline study that describes the multi-layer plastic packaging value chain, the related stakeholders, and the current opportunities, barriers and motivations to making the value chain more circular.

i. VALUE CHAIN

The resource loop for multi-layer plastic packaging includes eight value chain steps, i.e. from sorting to collection. In this chapter, each step is briefly explained.

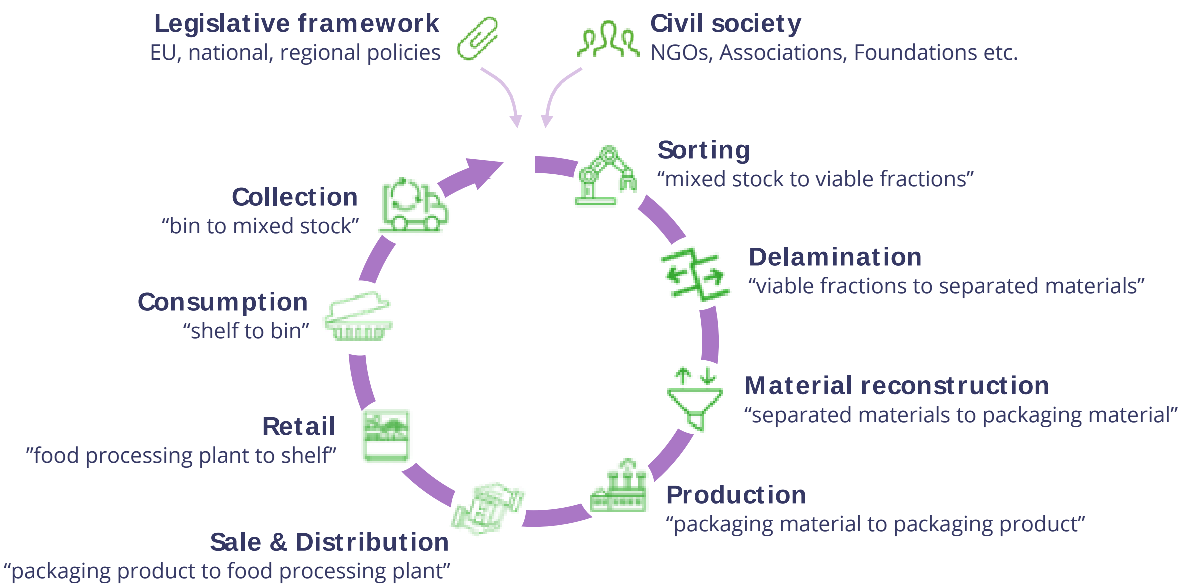


Figure 7: Multi-layer packaging value chain developed in MERLIN

The value chain of multi-layer plastic packaging was elaborated by the MERLIN consortium during the first months of the project. The first step is to extract relevant types of multi-layer packaging (rigid non-metallised, flexible non-metallised, flexible metallised) from collected waste streams in the **Sorting** step. The different layers contained in each piece of the sorted multi-layer packaging are then separated in the **Delamination** step. The valuable fractions of each layer are then recovered and valorised or transformed back into their base materials in the **Material reconstruction** step. The recycled base materials are used to produce new packaging products in the **Production step**, which are then distributed to food manufacturers in the **Sale & Distribution** step. After being filled with food, the resulting products are offered to private and commercial end users in the **Retail step**. End users buy and use the product in the **Consumption** step, and then dispose of the waste, which is collected in the **Collection** step. Having once completed the loop, the cycle can begin anew. The value chain is also affected by the **Legislative** framework laid out by policy and standardisation bodies at different governance levels and by activities from **Civil society**.

ii. STAKEHOLDERS

The value chain of multi-layer plastic packaging is extensive. Ambitions towards greater circularity - by improving resource efficiency and recycling quotas – will require a reconstitution of the entire value chain, including introducing new processes for sorting, delamination and material reconstruction. In every stage of the value chain there are several main actors involved in the material loop. The table below lists which stakeholders are relevant at each step of the value chain.

Stage of value chain	Key actors
Sorting	• Waste management companies • Municipalities • Recyclers • Sorting technology providers • Monitoring technology providers • Robotics industry
Delamination	• Raw material manufacturers • Converting companies • Treatment facilities • Base material producers
Material reconstruction	• Raw material manufacturers • Converting companies • Treatment facilities • Base material producers
Production	• Packaging manufacturers (PET and PE among others) • Packaging/filling machine providers (e.g. PET or PE in food sector) • Food safety authorities • Policy & standardisation bodies
Sale and distribution	• Packaging manufacturers • Packaging brand owners • Packaging converters • Traders/importers • Food manufacturers and processors • Packaging/filling machine providers

Grant Agreement No.: 101003883

Retail	• Food manufacturers and processors • Brand owners • Retailers • Packaging/filling machine providers
Consumption	• Consumers (private end users) • Commercial end users • Policy bodies setting reuse and recycling regulation
Collection	• Waste management companies • Municipalities • Voluntary schemes/authorities • Policy bodies setting reuse and recycling regulation

Table 5: Stakeholder clusters of multi-layer plastic packaging

Noteworthy in this context are also exploiters of delamination technology. The technology could be especially interesting in the work of recyclers, waste managers, plastic film producers and the chemical industry. In the case of material reconstruction, besides recyclers, waste managers, and the chemical industry, manufacturers of PET pellets, polyurethane and biopolymers can exploit the process step.

iii. MOTIVATIONS, OPPORTUNITIES AND BARRIERS

In order to achieve more circularity in multi-layer plastic packaging, it is important to develop an in-depth understanding of what drives or hinders stakeholders to act accordingly. In this chapter, we will discuss the most important motivations, opportunities and barriers identified by the MERLIN consortium partners. In order to ensure a common understanding of these terms, they are defined as follows:

- **Motivations**: Key targets or values that trigger or determine a stakeholders' behaviour
- **Opportunities**: Internal or external circumstances that make it favourable for stakeholders to act according to their motivations
- **Barriers**: Internal or external circumstances that prevent or inhibit stakeholders from acting according to their motivations

The motivations, barriers and opportunities of the key stakeholders will be analysed for each of the eight value chain steps. Each of these parts consists of a brief profile containing the most important aspects as well as an analysis drawing conclusions from these points. In order to categorise the different aspects, we make use of the PESTEL (Political, Economic, Social, Technological, Ecological, Legal) factors.

Sorting

"mixed stock to viable fractions"

Relevant stakeholders:

Waste management companies, municipalities, recyclers, sorting technology providers etc.

Motivations	**Opportunities**	**Barriers**
• Effective waste handling (preventing social and environmental harm from landfilling and incineration) • Reducing the rejection stream of multi-layer plastic packaging • Meeting recycling quotas • Meeting legal requirements • Mitigating climate change • Increasing purity of recycling output	• More recycling requires a growing feedstock • Better sorting yields higher product purity (higher prices for recycled materials) • Robotics as an enabler • Technological progress in sorting technology • Using AI for sorting purposes • Advancing identification technology	• Complexity of multi-layer plastic packaging design for sorting • Contamination of material streams • No defined harmonised multi-layer streams in the European Union • Inadequate pre-sorting by end-consumers • Lack of stakeholder harmonisation • Lack of consumer knowledge • Difficulties in waste stream identification • Missing insights in total volumes of multi-layer plastic packaging in waste streams

The sorting sector is motivated to improve the effectiveness of waste handling. By improving the sorting processes, the stakeholders want to reduce the rejection stream of contaminated or incorrectly sorted waste material. The waste management companies are also reacting to recycling quotas and legal requirements that are increasing the need to develop innovative and improved sorting. Lastly, the stakeholders want to reduce environmental pollution and contribute to climate change mitigation.

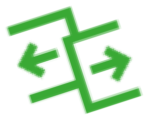
The stakeholders perceive an opportunity in increasing the amount and quality of sorted multi-layer plastic packaging waste to match a growth in recycling. These stakeholders expect that higher purity levels of the sorted waste could increase their value and price. Additionally, new technologies and innovations such as AI-supported robotics are seen as enabling technologies to overcome the technological, social and political challenges within the sorting sector.

The perceived barriers of our stakeholders lie within the complexity of multi-layer plastic packaging and the danger of contaminating material streams. Due to lack of standardisation or European harmonisation, and inadequate pre-sorting by end-consumers, the sorting of plastic packaging has become increasingly difficult. Both sorters and end-consumers are challenged with proper waste stream identification. In the end, sorting stakeholders - waste management companies, recyclers and municipalities - do not have sufficient monitoring and data insights to identify bottlenecks or to improve the sorting processes.

In summary, stakeholders involved in sorting are generally driven by economic and legal factors. Most of these factors have a strong link to potential ecological benefits and corresponding requirements. Technological progress is seen as an enabler that opens up economic opportunities, while at the same time current technological challenges (such as the potential contamination of waste streams, difficulties in reliable identification of different types of multi-layer packaging waste) present barriers to circularity. Furthermore, political factors (such as a lack of harmonisation in multi-layer streams and composition) and social factors (such as a lack of consumer knowledge on waste separation) present further barriers.

Delamination

"viable fractions to separated materials"



Relevant stakeholders:

Converting companies, treatment facilities, base material producers, raw material manufacturers

Motivations	Opportunities	Barriers
• Recover as much packaging as possible ("zero plastic waste") • Increasing purity of second raw material • Enabling creation of dedicated recycling applications for used material • Tapping into new markets	• Increased collaboration across the supply chain • New revenue streams • High availability of waste streams	• Low feedstock available • Heterogeneity in the current multi-layer composites • Few business cases of successful multi-layer packaging recycling

Converting companies and treatment facilities are motivated to recover as much packaging material as possible. By effectively delaminating the multiple layers of plastic packaging, they aim to increase the purity of secondary raw materials and to further enable the recycling application downstream. The delaminating process is a recent advancement in recycling technology and represents an opportunity for delaminating businesses to tap into emerging markets.

The stakeholders see opportunities in increased and improved collaboration across the supply chain for better recycling processes. The economic incentives lie in new revenue streams and in a higher availability of waste streams to create economies of scale.

Due to insufficient sorting or material losses of multi-layer plastic packaging, the feedstock is currently too low to incentivise economically viable delamination processes. The heterogeneity of waste material imposes another barrier on delamination. Only a few businesses have emerged that showcase successful delamination and recycling of multi-layer plastic packaging. The current market is in a nurturing phase that will soon be developed further.

Delamination represents both an economic and technological challenge. The technology might be available, but the financial business case is not there yet, given the investment costs for equipment and infrastructure, but especially due to a low feedstock of separately collected and uncontaminated waste from multi-layer plastic packaging. With economic incentives, the technological barriers to delaminate can be overcome.

Material reconstruction

"separated materials to packaging material"

Relevant stakeholders:

Converting companies, treatment facilities, base material producers, raw material manufacturers

Motivations	Opportunities	Barriers
• Recover as much packaging material as possible ("zero plastic waste") • Increasing purity of second raw material • High demand for recycled plastics • Environmental savings when compared to fossil-fuel based raw materials	• Increased collaboration across the supply chain • Enhancing the product portfolio • New business activity of material reconstruction • Reducing commodity price volatility	• Low or diverse material quality • Danger of contamination • Harmonisation in legislation required • Missing industry standards in multi-layer packaging

Converting companies, treatment facilities and base material producers are driven by a trend towards "zero plastic waste" goals and expectations to increase the purity and quality of secondary raw material. Due to consumer-driven demand and growing efforts for sustainable business, the stakeholders in material reconstruction are motivated by a need to reduce environmental footprints and to generate sustainable impact.

Converters and treatment facilitators identify several opportunities in the advanced recycling of multi-layer packaging. Increasing collaboration across the supply chain should minimise risks of commodity price volatility and increase efficiency throughout the value chain. With the recycling of materials, converters can enhance their product portfolio with a product line of recycled base materials.

A common theme of the barriers to material reconstruction is the low or diverse material quality of the resource stream. The stakeholders perceive a contamination risk with plastic products that could make them unsuitable for e.g. food packaging or medical appliances. The stakeholders also criticise missing industry standards in multi-layer packaging that slow down recycling efforts towards a circular economy in the plastics sector.

The stakeholders of material reconstruction are driven by economic factors and the political and environmental pressure to start new recycling processes for multi-layer plastic packaging. Similarly to the previous value chain step, economic incentives for market entries could increase the acceleration to recycle multi-layer plastic packaging.

Production

“packaging material to packaging product"

Relevant stakeholders:

Packaging manufacturers, Packaging/filling machine providers, food safety authorities, policy & standardisation bodies

Motivations	Opportunities	Barriers
• Offer products at competitive prices • Being (perceived as) a “green” company • Fulfil (new) customer demands • Tap into new markets (growth & stability)	• Perceived as sustainable by customers • Increased supply chain collaboration • Fulfilling customer wishes for more recycled content in packaging • Potential reduction in internal costs • Enhance product portfolio/customer groups • New revenue streams • Improved brand value • Compliance with regulation • Circular products can create competitive advantage	• Stable and reliable quality and quantity supply of material • Customers are very price sensitive • Potential lack in convenience design • Higher costs of recycled materials

The producers want to offer their (recycled) multi-layer plastic packaging at competitive prices. Due to the increased demand of sustainable or green packaging solutions, packaging producers want to be perceived as a green and environmentally friendly company in order to fulfil their customer demands. In this step, producers are able to tap into new markets and green customer segments.

Advancing the stakeholders’ sustainability agendas can be helpful in both diversifying the company and producing multi-layer plastic packaging. A common theme is the enhanced collaboration between suppliers and buyers for optimised supply chain management. The packaging manufacturers see the potential to reduce internal costs and to create new revenue streams while improving the company’s brand value. The stakeholders are strategically scouting new prospects and opportunities to create competitive advantage. Higher recycling rates and optimised waste streams allow manufacturers to more easily comply with regulation.

The producers are concerned that secondary raw materials could endanger the integrity and overall quality of their end products. Furthermore, the stakeholders are concerned with high price sensitivity within the customer base and perceive higher costs for recycled material. A final barrier lies in the material alterations that reduce the convenience and advantageous characteristics of multi-layer plastic packaging.

For the producers, the main factors that influence change towards new recycling processes and technologies, are economic factors, i.e. lowering production cost and price sensitivity. Environmental, social and political

Grant Agreement No.: 101003883

pressure can push new developments in the recycling of multi-layer plastic packaging. The need to comply with future legislation and new customer demand of green products could accelerate efforts to become more resource-efficient.

Sale & Distribution

"packaging product to food processing plant

Relevant stakeholders:

Packaging manufacturers, packaging brand owners, traders/importers, packaging/filling machine providers

Motivations	Opportunities	Barriers
• Offer products at competitive prices • Being (perceived as) a "green" company • Fulfil (new) customer demands • Tap into new markets (growth & stability)	• Perceived as sustainable by customers • Increased supply chain collaboration • Fulfil customers wishes for more recycled materials in packaging • Potential reduction in internal costs • Enhance product portfolio/customer groups • New revenue streams • Improved brand value • Compliance with current/future legislation on recycling • Circular products have a competitive advantage	• Customers are very price sensitive • Potential lack in convenience and design • Stable and reliable quality and quantity supply of material • Higher costs of recycled materials

Distributors of multi-layer plastic packaging want to offer their recycled products at competitive prices for economic viability. They are directly in contact with food processors that fill goods and food into packaging for retail. The customer demands are therefore crucial and need to be met. One motivation here is also to be perceived as a distributor of more sustainable or green plastic packaging – again, to meet the aforementioned customer demands.

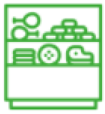
This being said, the stakeholders in sales and distribution see a diversification opportunity in sustainable leadership. With increased supply chain collaboration there is the opportunity to supply the market with multi-layer plastic packaging from successfully recycled materials coming from within their own industry. With this enhanced product portfolio, the companies expect to improve their brand values and reduce internal costs for supply materials. Lastly, with increased ambitions for recycling and recovery of plastic material, these stakeholders also seek to comply with the current - but most of all future - legislation and regulation on plastic recycling.

Packaging manufacturers, brand owners, and distributors, as many other stakeholders, see the high price sensitivity in the plastic packaging sector. Changes in the value chain due to increased recycling efforts might change the product profile of multi-layer plastic packaging and be less convenient in use. The stakeholders are concerned with the barriers of stable supply in quality and quantity to fulfil customer needs, and the higher production or management costs of recycled materials.

In sales and distribution, the main factors that influence change towards new recycling processes and technologies, are economic factors, i.e. lowering production cost and price sensitivity. Environmental, social and political pressure can push new developments in the recycling of multi-layer plastic packaging. The need to comply with future legislation and new customer demand of green products could accelerate efforts to become more resource-efficient.

Retail

"food processing plant to shelf"



Relevant stakeholders:

Food manufacturers & processors, brand owners, retailers, packaging/filling machine providers

Motivations	Opportunities	Barriers
• Being (perceived as) a "green" company • Fulfil (new) customer demands • Reduce carbon footprint • Enhanced credibility as company that enable consumers to behave sustainably	• Brand loyalty • Increased demand for sustainable packaging from eco-conscious consumers • Consumers potentially willing to pay more for more sustainable products • Distinguish products/sustainability efforts from competitors • Keep performance quality of multi-layer packaging while lowering environmental footprint • CSR has an increasing role in companies' strategies • Nudge certain consumer behaviour through different packaging options	• Food safety requirements • Potentially unsatisfactory quality and technical performance • Difficult to inform or advertise benefits of recycled packaging • Purchasing decisions based on habit and familiarity • Packaging is only one of many factors to increase sustainability (not the highest priority) • Limited space on packaging to inform consumers about sustainability • Customer decisions might be influenced by perceptions on what is sustainable

Food manufacturers, brand owners and retailers also experience the need to enhance their sustainability credentials as a business. Retailers are motivated by being perceived as green or sustainable, and thus their products need to comply with new product requirements, e.g. recycled content or sustainably sourced material. Retailers are driven by the need to reduce their carbon footprints and the need for to be credible as a sustainable business.

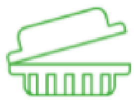
The expected rewards and opportunities lie in increased brand loyalty and higher demand for sustainable packaging products. With strategies of diversification, retailers could set themselves apart from competitors and successfully distinguish themselves. In an ideal case, this diversification could also allow the retailers to demand higher prices. One of the main opportunities lies with the decoupling of packaging quality and performance from the negative environmental impact of plastic packaging. MERLIN consortium stakeholders perceive that corporate social responsibility (CSR) are becoming more important for companies, and companies therefore allocate more resources to CSR activities. An addition opportunity for retail stakeholders is the ability to nudge end-consumers to choose alternative and environmentally friendly packaging options.

The main barriers in the retail step are connected to quality concerns and food safety. The stakeholders are concerned that the packaging does not fulfil consumer requirements and that engrained consumption patterns and habits are barriers to efforts to recycle and change packaging. Finally, there are concerns that end-users do not perceive sustainable packaging as an effective way to change their sustainable consumption style. They may be influenced by other trends, such as the perceived sustainability of packaging-free goods.

Social and economic factors prevail in the retail value chain step. Retail sustainability strategies in communication, customer perception and the price sensitivity will determine the willingness to sell and buy products that are made of recycled multi-layer plastic packaging. This issue is not specific to multi-layer plastic packaging but applies to any ‘green’ packaging type.

Consumption

“shelf to bin"



Relevant stakeholders:

Consumers (private end users), Commercial end users, policy bodies setting reuse and recycling regulations

Motivations	**Opportunities**	**Barriers**
• Living more sustainably (with as little behaviour/ lifestyle changes as possible) • Being (perceived as) a "green" or conscious individual • Fulfil (new) customer demands (commercial end users) • Be informed about the environmental impact of consumption decisions • Reduce carbon footprint	• Increased choice of packaging types • Increase in eco-conscious purchasing by peers influence own behaviour • Increase in interest in sustainability • Increased ability to live more sustainably easily	• Higher costs • Health concerns • Food safety concerns • Unable to identify different kinds of packaging and their advantages & disadvantages (pre-consumption) • Information on the potential recyclability of different packaging is not easily available (post-consumption)

Private and commercial end-consumers are driven by sustainable lifestyle and sustainable consumption patterns arising from social and ecological pressures. New requirements of sustainable consumption drive change and motivate the stakeholders to change their behaviour. They are motivated by the need to be ecologically conscious and to be informed about the environmental footprints and impacts of consumption and production (of plastic packaging waste).

The increasing availability of diverse sustainable packaging solutions provide consumers with an opportunity to alter their purchasing behaviour. These solutions have the advantages of safety and product quality as well as a reduction in the environmental impact of the packaging good. The opportunity lies in bringing both convenience and sustainability together, which allows consumers to make easy and sustainable choices.

Nonetheless, higher costs and prices are a concern for consumers, as are concerns about food safety when using recycled material for food packaging.

Furthermore, consumers are required to be able to identify sustainable packaging over conventional packaging products. Thus, sustainable consumption choices require knowledge and consumer education.

In summary, consumption behaviour is mainly driven by social, environmental and economic considerations. Common perception and consumer information will determine the success of recycled multi-layer plastic packaging, while buying, consuming and disposing.

Collection

"bin to mixed stock"

Relevant stakeholders:

Waste management companies, municipalities, voluntary scheme authorities, policy bodies setting reuse and recycling regulation

Motivations	Opportunities	Barriers
• Meet waste reduction goals/legislation • Increase purity of collected waste to increase valorisation potential • Empower citizen and households to effectively sort waste • Effective waste handling (preventing social and environmental harm by landfilling, incineration) • New revenue streams	• New market for multi-layer plastic packaging waste • A new way to help meet waste reduction goals or requirements • Can convince consumers to separate waste better, knowing that it has benefits because of technological feasibility • Compliance with current & future environmental regulation	• Lack of consumer concern about separating waste • Lack of consumer knowledge of how to separate waste • Lack of convenience (e.g. bins, space) for consumers to separate waste • Inadequate pre-sorting by end consumers • Recycling by waste management companies is not mandatory/regulated everywhere

The waste managers, collection companies and municipalities are motivated to become more resource efficient by the need to meet waste reduction goals and comply with national and international waste legislation. By increasing the purity of material, the stakeholders are able to also increase the value and selling price.

Increased awareness and education among households to separate waste at source would benefit the collection and sorting steps in the plastic packaging value chain. The collection stakeholders are motivated by preventing social and environmental harm and to effectively handle waste and turning them into valuable resources again.

Collection stakeholders can contribute to increasing the quantity and quality of a multi-layer plastic waste feedstock that allows for further efficient recycling. This way, the stakeholders can meet their waste reduction goals and recycling quotas and comply with environmental regulation.

Effective sorting at source is conditional to successful recycling. Therefore, stakeholders in collection face barriers of insufficient consumer awareness and education of waste disposal and sorting. It is the lack of convenience in disposing waste that makes effective waste management and recycling more difficult. A lack of an EU mandatory recycling regulation (over recovery and landfilling) imposes barriers to effective and innovative recycling of multi-layer plastic packaging.

The main factors that could enable improvements of multi-layer plastic packaging recycling are mostly economic and technological in this value chain step. More transparency in monitoring, effectiveness of separation and economic efficiency is required to enhance recycling.

iv. CONCLUSION

Due to its complex structure and heterogeneous composition, recycling multi-layer plastic packaging remains a major challenge. The above analysis of motivations, opportunities and barriers of increasing circularity gives a comprehensive overview of what drives change in this area. The required change for each of the value chain steps lies in one of two perspectives. The first perspective, most relevant in the Sorting, Delamination, Material reconstruction and Collection steps, focuses on technological and processual innovation to recycle multi-layer plastic packaging waste. The second perspective is focused on measures to facilitate acceptance, utilisation and promotion of the resulting materials and products. This is most relevant for the value chain steps Production, Sale & Distribution, Retail and Consumption.

Stakeholders in the first area, seeking innovation in recycling multi-layer plastic packaging, are mainly driven by economic and environmental incentives. The prospect of tapping into new revenue sources for existing waste streams and at the same time significantly reducing harmful environmental effects by cutting incineration for energy recovery or even landfilling is a strong stimulus to explore new approaches. The challenges these stakeholders face are mostly technological and regulatory issues. The application of new technologies and processes is key to developing effective, resource-efficient and scalable procedures for the valorisation of multi-layer plastic packaging waste. In addition, regulatory changes may be required to support and enhance the introduction of such new procedures as well as incentivise the waste and recycling industries to take them up. Another factor, mostly relevant to the collection step, is the social dimension. As consumers play a crucial part in separating and recovering used packaging, education and incentivisation to do so conscientiously is an important lever for higher waste recovery rates.

Stakeholders in the second area are also mainly driven by economic incentives, but in a different way. They react to the pull factor of an increasing demand for more sustainable products by end consumers while having very limited room for cost and price increases to meet this demand. By providing more sustainable packaging, all stakeholders build up their image of acting in a "greener" way while retaining their market shares or standard of living, respectively. The barriers are mainly technical, such as ensuring compliance with legal requirements on food safety and matching consumer expectations on product properties and appearance as well as keeping price increases at a minimum.

All MERLIN project activities aim to support stakeholders in realising opportunities and overcoming barriers. Close collaboration of different stakeholders across the value chain and active engagement of all relevant stakeholder groups throughout the project duration are important factors in bringing about the technological, social, political and behavioural changes necessary to increasing circularity in the multi-layer plastic packaging industry.

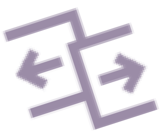
4. OUTLOOK

A historic moment came in March 2022 when the UN Environment Assembly, representing 175 nations, agreed to draw up an international legally binding treaty on plastic pollution by 2024. The landmark agreement was touted as "the most important international environmental deal since Paris [the UN climate agreement in 2016] (UNEP, 2022)". The agreement in 2024 should set targets and pathways to end plastic pollution. One main consideration must be to keep plastics in the value chain at the end of life and reduce the use of virgin materials in plastic production.

The EU is heading in this direction: Currently, four million tonnes of recycled plastic are used in new products in the EU. Almost half is re-used for building and construction products, while a quarter is re-used in packaging products. Particularly noteworthy is that the recycling rate for post-consumer plastic waste in the EU is increasing faster than any other treatment option, including energy recovery (PlasticsEurope, 2019). This indicates movement in the right direction of a more circular plastic value chain.

Multi-layer plastic packaging presents a special challenge in plastic recycling, as the various layers need to be separated and treated differently before being reused. The MERLIN project is currently developing and testing technological solutions at multiple stages of this value chain, especially in sorting, delamination, material reconstruction, production and consumption.

In the sorting stage, MERLIN is developing an optical system that will identify the material from each main polymer layer in multi-layer structure polymers. In addition, artificial intelligence and robotics are being combined to identify and classify packaging into the categories of rigid packaging, non-metallised flexible films, and metallised flexible films from the waste stream.



Delamination of rigid packaging is being tested with PET depolymerisation via solvolysis processes for multi-layer matrices. For non-metallised flexible packaging, delamination using traditional and green solvents is being tested. For metallised flexible packaging, aluminium is being recovered from metallised flexible films using a solvent-based process to dissolve polymers and adhesives under mild conditions. Aluminium can thus be mechanically separated, which preserves its quality without substantial oxidation. The PET and PO fractions in the structure will be separated and recovered.

In the material reconstruction stage after depolymerisation and purification, MERLIN is repolymerising monomers and prepolymers into PET lab scale. The project will also upcycle PET and PE/PP fractions recovered from the delamination processes. The goal is to have a maximum deviation of 10-15 % in mechanical properties or processability compared to virgin materials used in flexible and rigid packaging.

In addition, MERLIN is developing and validating packaging from recycled PET and PE/PP, ensuring at least the same quality and safety requirements as that of the initially separated materials. The packaging should be cost-effective and from 100 % recycled material for both flexible and rigid packaging in the food sector. These will take the forms of flow packs, bottles, pots and thermoform trays. They will be benchmarked against their counterparts made from virgin materials in terms of oxygen transmission and water vapor transmission rates. In order to ensure a circular end of life, this recycled multi-layer packaging will be recycled a second time using the delamination processes outlined above.

Accompanying these technological innovations, MERLIN is developing a decision support system for waste managers and packaging industry stakeholders. The system will help users identify and select the best processes and technologies for separation and recycling based on parameters set by the user. In addition, packaging companies will be able to use the system to compare the use of recycled and virgin materials in their product designs. Finally, to aid end users in their purchasing decision of food products in recycled or non-recycled packaging, MERLIN will develop a QR code to be added to a rigid pot. The code provides consumers with data about the packaging materials and production process.

Alongside MERLIN, there are other interesting initiatives to keep an eye on: For example, MORE is a digital platform that monitors the re-integration of recycled polymers into products in the EU. CEFLEX is a multi-stakeholder initiative looking for circular solutions for flexible packaging. Circular Plastics Alliance aims to boost the EU market for recycled plastics to up to 10 million tonnes by 2025. Fraunhofer IVV has multiple research projects on food packaging made of composite materials, which is often multi-layered (PET, PE, PP, EVOH, PA, metallisation). The projects look to thermally recycle these layers and maintain the material's properties even after several life cycles (Fraunhofer IVV, n.d.).

Technological innovations notwithstanding, changing an entire value chain is a complex challenge. What is increasingly needed in Europe is closer policy alignment on recycling, plastic waste, and food safety requirements between the EU and national levels. This will help to some extent to address the significant uncertainty regarding the market for recycled plastics - including recycled multi-layer plastic packaging - and demand for technological solutions. This is a particular concern when considering price competitiveness of recycled versus virgin materials. In order to bring these innovations from the lab to large scale industrial application, we need to build confidence in the market through transparent, harmonised and supporting policies. This may require politically sensitive decisions – for example, to price virgin materials with internalised environmental costs. Because of these complex interlinkages between waste policy, food safety regulation, industrial technology, retail business models, and consumer behaviour, decisions made by stakeholders in an attempt to increase circularity in the multi-layer plastic packaging value chain would likely

Grant Agreement No.: 101003883

be more successful when undertaken in tandem with other stakeholders and initiatives. In parallel to testing technical solutions, MERLIN is actively engaging key stakeholders so that they can understand the other actors along the value chain, exchange with them, and collaborate on mutually beneficial strategies of bringing solutions into the mainstream.

References

Bauer, A.-S., Tacker, M., Uysal-Unalan, I., Cruz, R. M. S., Varzakas, T., & Krauter, V. (2021). Recyclability and Redesign Challenges in Multilayer Flexible Food Packaging—A Review. *Foods*, *10*(11), 2702. https://doi.org/10.3390/foods10112702

Bavarian Research Alliance. (2021, September 1). *EU funded project CIRCULAR FoodPack to develop a system for circularity of packaging for direct food contact applications*. BayFor Homepage. https://www.bayfor.org/en/press/press-releases/detail-en/3981-eu-funded-project-circular-foodpack-to-develop-a-system-for-circularity-of-packaging-for-direct-food-contact-applications.html

Butler, T. I., & Morris, B. A. (2016). 17—PE-Based Multilayer Film Structures. In J. R. Wagner (Ed.), *Multilayer Flexible Packaging (Second Edition)* (pp. 281–310). William Andrew Publishing. https://doi.org/10.1016/B978-0-323-37100-1.00017-X

Ellen MacArthur Foundation. (2014). *Towards the Circular Economy—Acclerating the scale-up across global supply chains* (p. 41). https://ellenmacarthurfoundation.org/publications

European Commission. (n.d.). *EU Plastics Strategy*. European Commission. Retrieved February 11, 2022, from https://ec.europa.eu/environment/strategy/plastics-strategy_en

European Commission. (2014, July). *Environment: Higher recycling targets to drive transition to a Circular Economy with new jobs and sustainable growth*. https://ec.europa.eu/commission/presscorner/detail/en/IP_14_763

eurostat. (2021, October). *Packaging waste statistics*. Eurostat Statistics Explained. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Packaging_waste_statistics

Fraunhofer IVV. (n.d.). *Recycling von Mulitlayer-Verpackungen—Forschungsprojekt*. Fraunhofer-Institut Für Verfahrenstechnik Und Verpackung IVV. Retrieved March 24, 2022, from https://www.ivv.fraunhofer.de/de/recycling-umwelt/multilayerrecycling.html

Kaiser, K., Schmid, M., & Schlummer, M. (2017). Recycling of Polymer-Based Multilayer Packaging: A Review. *Recycling*, *3*(1), 1. https://doi.org/10.3390/recycling3010001

Material Economics. (2022). *Europe's Missing Plastics*. https://www.agora-energiewende.de/en/publications/closing-the-loop/

PlasticsEurope. (2019). *The Circular Economy For Plastics—A European Overview*. PlasticsEurope AISBL. https://plasticseurope.org/knowledge-hub/the-circular-economy-for-plastics-a-european-overview/

Ramos, L., Berenstein, G., Hughes, E. A., Zalts, A., & Montserrat, J. M. (2015). Polyethylene film incorporation into the horticultural soil of small periurban production units in Argentina. *Science of The Total Environment*, *523*, 74–81. https://doi.org/10.1016/j.scitotenv.2015.03.142

Sartor, O., Azais, N., Burmeister, H., Münnich, P., & Witecka, W. (2022). *Mobilising the circular economy for energy-intensive materials—How Europe can accelerate its transition to fossil-free, energy-efficient and independent industrial production*. Agora Industry. https://www.agora-energiewende.de/en/publications/closing-the-loop/

Soares, C. T. de M., Ek, M., Östmark, E., Gällstedt, M., & Karlsson, S. (2022). Recycling of multi-material multilayer plastic packaging: Current trends and future scenarios. *Resources, Conservation and Recycling*, *176*, 105905. https://doi.org/10.1016/j.resconrec.2021.105905

UNEP. (2022, March 2). *What you need to know about the plastic pollution resolution*. United Nations Environment Programme. https://www.unep.org/news-and-stories/story/what-you-need-know-about-plastic-pollution-resolution

Walker, T. W., Frelka, N., Shen, Z., Chew, A. K., Banick, J., Grey, S., Kim, M. S., Dumesic, J. A., Van Lehn, R. C., & Huber, G. W. (2020). Recycling of multilayer plastic packaging materials by solvent-targeted recovery and precipitation. *Science Advances*, *6*(47), eaba7599. https://doi.org/10.1126/sciadv.aba7599

Wecker, K. (2018, October 12). Plastic waste and the recycling myth. *Deutsche Welle*. https://www.dw.com/en/plastic-waste-and-the-recycling-myth/a-45746469

WEF, Ellen MacArthur Foundation, & McKinsey & Company. (2016). *The New Plastics Economy—Rethinking the future of plastics*. https://ellenmacarthurfoundation.org/the-new-plastics-economy-rethinking-the-future-of-plastics