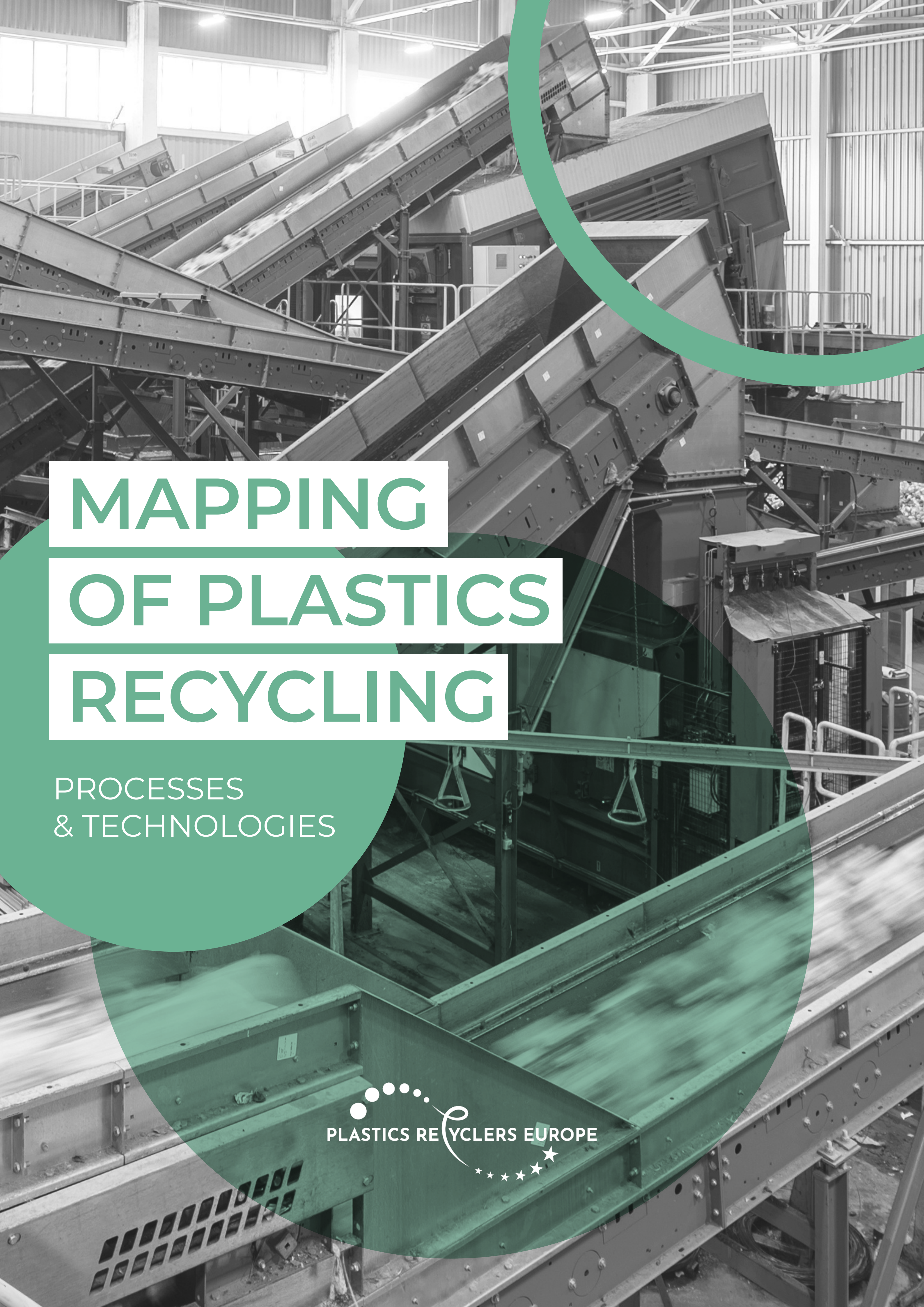


MAPPING OF PLASTICS RECYCLING

PROCESSES & TECHNOLOGIES

PLASTICS RECYCLERS EUROPE

DISCLAIMER

This report by Plastics Recyclers Europe (PRE) is for informational purposes only. PRE conducted this mapping exercise using the most robust and accurate information available, aiming to present the technologies and processes most widely implemented in recycling facilities. Where relevant, emerging technologies are also included for their potential value in advancing plastic recycling. While care was taken to ensure accuracy, PRE makes no guarantees regarding completeness or suitability for specific uses and assumes no liability for actions taken based on this report. For the most current data on production volumes and figures, please consult the PRE website and official publications. Reproduction or distribution without written permission is prohibited.

2025

Table of content

List of acronyms and abbreviations

2D	Two-dimensional
3D	Three-dimensional
ABS	Acrylonitrile Butadiene Styrene
AI	Artificial Intelligence
ASR	Automotive Shredded Residue
ATF	Authorised Treatment Facilities
BHET	Bis (2-hydroxyethyl) Terephthalate
CEAP	Circular Economy Action Plan
CFC	Chlorofluorocarbon
CR	Chemical Recycling
DMT	Dimethyl Terephthalate
DRS	Deposit Return System
EC	European Commission
EFSA	European Food Safety Authority
EG	Ethylene Glycol
ELV	End-of-Life Vehicles
ELVD	End-of-Life Vehicles Directive
EOL	End-of-Life
EPR	Extended Producer Responsibility
EPS	Expanded Polystyrene
EU	European Union
HDPE	High Density Polyethylene
LDPE	Low Density Polyethylene
LIBS	Laser-Induced Breakdown Spectroscopy
MR	Mechanical Recycling
MRF	Materials Recovery Facilities
MS	Member State
MSW	Municipal Solid Waste
NIR	Near Infra-Red
PA	Polyamide
PAH	Polycyclic Aromatic Hydrocarbon
PC	Polycarbonate
PCB	Printed Circuit Boards
PE	Polyethylene
PES	Polyester
PET	Polyethylene Terephthalate
PLA	Polylactic Acid
PO	Polyolefin
POPs	Persistent Organic Pollutants
PP	Polypropylene
PPWR	Packaging and Packaging Waste Regulation
PRE	Plastics Recyclers Europe
PRF	Plastics Recovery Facility
PS	Polystyrene
PU	Polyurethane
PVC	Polyvinyl Chloride
RoHS	Restriction of Hazardous Substances
SDA	Small Domestic Appliances
SLF	Shredder Light Fraction
SoC	Substances of Concern
SSP	Solid-State Polycondensation
SVHC	Substance of Very High Concern
TEE	Temperature Exchange Equipment
TPA	Terephthalic Acid
UV	Ultraviolet
WEEE	Waste Electrical and Electronic Equipment
XRF	X-Ray Fluorescence

Executive Summary

This report by Plastics Recyclers Europe (PRE) provides a comprehensive overview of the current landscape of plastic waste recycling technologies and processes in Europe. It focuses and elaborates on three main recycling approaches: mechanical, dissolution, and chemical recycling, applied across key plastics waste streams including Packaging, Electrical and Electronic Equipment (EEE), End-of-Life Vehicles (ELV), and Building and Construction.

Based on extensive interviews, data collection, site visits, and thorough analysis of patents and scientific literature, the report offers a detailed examination of the entire recycling chain, from waste collection to sorting and recycling. It also presents an analysis of market dynamics and waste stream characteristics, along with a detailed assessment of sorting and recycling technologies.

A central feature of the report is the evaluation of the implementation of recycling technologies at industrial scale using a 'traffic light' system (see Box 1), categorising their level of industrial implementation from emerging to widely adopted. The findings emphasise that the overall efficiency of recycling systems is closely linked to the effectiveness of sorting and separation technologies within the recycling process, such as near-infrared (NIR) sorting, sink-float separation, windsifting, and AI-driven systems.

The report outlines the specific characteristics of each recycling method. Mechanical recycling remains the most established, using processes like grinding, washing, drying, and extrusion to produce recyclates in the form of pellets or flakes. Dissolution recycling employs solvents to dissolve polymers and remove contaminants, offering high-purity recyclates, particularly for hard-to-recycle plastics. Chemical recycling, through techniques such as pyrolysis, gasification, and depolymerisation, enables the breakdown of plastic waste at a molecular level to produce new raw materials from mixed and contaminated waste streams.

By providing a clear picture of current capabilities, challenges, and technological advancements, this report serves as a critical resource for stakeholders aiming to strengthen Europe's plastic recycling infrastructure and drive progress toward a circular economy for plastics.

User Guide

The report is organised into the following sections:

- **Introduction**: an overview of the plastics and recycled plastics markets will be given, followed by an overview of the leading plastics waste streams and their characteristics. Market figures for both mechanical, dissolution and chemical recycling are also reported in this section.

- **Sorting process:** firstly, the *Modules* section will provide an overview of the three main units common to each sorting process, specifically collection, sorting and size reduction. Then, the *Sorting Technologies* section will dive into the specific technologies within each unit per single stream. The implementation level of specific sorting technologies (e.g., NIR for packaging) follows the logic described in Box 1.

- **Recycling processes (mechanical, dissolution and chemical):** similar to the previous chapter, in the *Modules* section, we will give an overview of the main units usually present in mechanical, dissolution and chemical recycling processes. Finally, the *Recycling Technologies* section will illustrate the specific recycling technologies within each process (i.e., mechanical, dissolution and chemical) per single stream. The specific recycling technologies will follow the same identification as the ones for the sorting process, as described in Box 1.

The specific processes (e.g., recycling of rigid polyolefins, flexibles, WEEE/ELV plastics, etc.) are represented visually via exemplary schemes, which follow the legend below (a green box indicates the material, a yellow one a step that is optional in the process and the blue one a technology which is part of the standard process):

Material type | Optional step | Technology

LEVELS OF IMPLEMENTATION AT INDUSTRIAL SCALE

In the report, the level of implementation at industrial scale is reported for specific technologies by **highlighting them using a traffic light system** that is linked to semiquantitative ranges based on industry knowledge, as explained below:

Red: 0 % technology implementation, i.e., a technology currently under lab-scale development and not used by recyclers at the industrial scale.

Orange: <10 % technology implementation, i.e., a technology currently under development and used by few to very few recyclers at industrial scale.

Yellow: 10-25 % technology implementation, i.e., a technology with a low level of implementation at industrial scale.

Light green: 25-55 % technology implementation, i.e., a technology with a medium level of implementation at industrial scale.

Dark green: >55 % technology implementation, i.e., a technology widely implemented at industrial scale.

Box 1. System for the level of implementation of the sorting and recycling technologies described in the report.

INTRODUCTION

Plastics Recycling: How Does it Work?

Plastics are materials made of polymers, which are composed of long chains of repeating smaller units called monomers. These monomers are ‘linked’ together through a process called polymerisation. This process leads to form a polymer, giving the material strength, flexibility, and durability. To transform a polymer into a usable plastic product, the polymer is first compounded with additives and then converted into shapes through processes such as extrusion or molding. Plastics are widely spread materials, from packaging to electronics, because they hold many favourable properties, being lightweight, durable, flexible, and resistant to chemicals. However, these properties also cause plastics to take hundreds of years to break down. As such, recycling is important to help reduce plastic waste and protect the environment. The schemes below illustrate the recycling technologies that will be elaborated in the report.

The Market for Plastics

The plastics recycling industry plays a pivotal role in shifting from a linear to a circular economy model by keeping valuable resources in the loop, reducing the dependency on virgin raw materials, and decreasing the EU's carbon footprint. In this context, effectively recycling plastics supports the EU's climate neutrality goals by 2050.

In 2022, the European plastics production came to a total of 58.7 Mt,[1] of which 54 Mt were converted into plastic products and parts, mainly for the packaging sector (39 %), followed by construction (23 %) and other applications (16 %), with automotive, electrical and electronics sectors covering only the 8 % and 6 % of EU plastic conversion, respectively, as shown in Figure 1 below.

Mechanical recycling statistics

As for mechanically recycled plastics, the installed capacities were mapped for EU27+3[2] in the report '*Plastic Recycling Industry Figures 2024*',[3] which shows that these reached 13.5 million tonnes in 2024, split between 850 active companies. The share of the total installed recycling input capacity is shown in Figure 2, categorised per polymer type and country, respectively. As displayed in Figure 2, flexibles continue to lead in the installed recycling capacities, with close to 3.5 million tonnes reported in 2024. Hence, Polyethylene (PE) and Polypropylene (PP) flexibles, Polyethylene Terephthalate (PET), and High-density Polyethylene (HDPE) and PP rigids hold the most significant proportion of nearly 80 % of the total input capacity in EU27+3 countries.

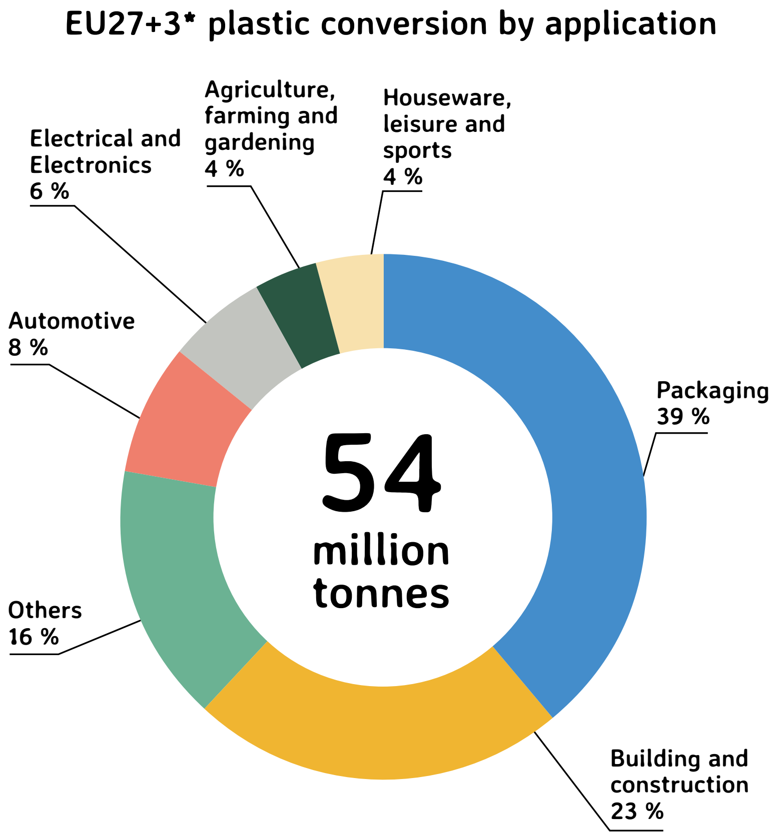


Figure 1. Total of EU27+3 plastic converted in articles (54Mt) in 2022, divided by end sectors.

While new developments are foreseen in the field of Waste Electrical and Electronic Equipment (WEEE) and End-of-Life Vehicles (ELV) plastics recycling, ahead of the announced proposal to introduce recycled content targets for these applications, as for now, the 2024 estimated capacity for ELV and WEEE plastics was around 800 Kt, representing almost 6 % of the total capacity in EU27+3 countries. For this stream, which includes the treatment of, among others, PP, Polystyrene (PS) and Acrylonitrile Butadiene Styrene (ABS), France and the United Kingdom hold the highest installed capacities. In contrast, Spain and Germany hold the highest installed capacities in the the PS and Expanded Polystyrene (EPS) groups.

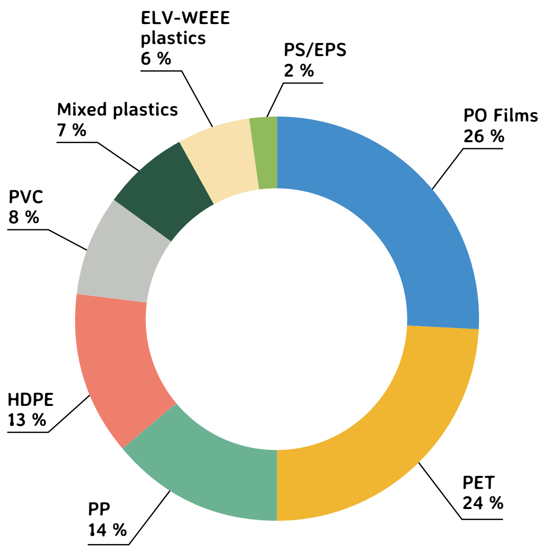
Dissolution recycling statistics

According to public announcements, this technology is foreseen to be used in several pilot plants in Europe that are expected to begin operating in the coming years. The targeted polymers are diverse, ranging from multilayer flexible packaging to PET, PS, PP and PE.

Chemical recycling statistics

In 2024, the estimated chemical capacity for recycling plastics in the EU27+3 region was around 190 kilotonnes. Pyrolysis was the dominant technology, and mixed polyolefins were the most targeted fraction. Additional plants are in the commissioning or pilot stage and are expected to begin operating in the coming years.

Share of installed recycling input capacity in EU27+3*, per polymer type



Total installed recycling input capacity in EU27+3, per polymer and per country (%), 2024

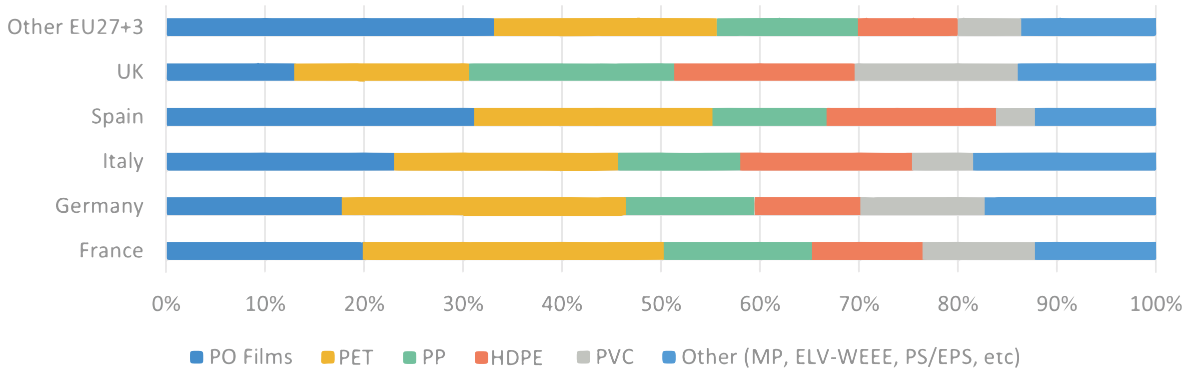


Figure 2. Share of total installed recycling input capacity in EU27+3, per polymer type (top plot) and per polymer, per country (bottom plot).

Plastic Types in Waste Streams

Market overview

This section introduces the different types of plastics that serve as the primary input to European plastic recycling companies. The table below provides an overview of the installed input capacity and production specifically for polymer streams that are typically processed through mechanical recycling (MR). Data for other recycling technologies is not yet available. It should be noted that the following information refers only to established plastic recycling streams in Europe. Plastics not currently recycled at scale in Europe are not considered (e.g., PET films, PVC films, etc.).

In the following sections, general characteristics of these materials will be presented, along with pictures of articles and products typically made out of them. Finally, for each category (i.e., plastic packaging, WEEE and ELV, and building and construction), some statistical figures are given regarding the type of input that reaches plastics recyclers. Please note that such figures refer only to plastic waste that goes through mechanical recycling, while lack of data exists for chemical and dissolution recycling. PRE collected these figures in its yearly statistical and technical surveys, which are carried out by its members to gather specific data on recycling processes and related technologies from the different plastics recycling streams in the EU27+3 countries.

POLYMER STREAM	INPUT (WASTE) PROCESSED KT	PUT (RECYCLATE) PRODUCTION KT
PO films	2680	1960
PET	2800	2015
HDPE	1300	970
PP	1325	965
PVC*	875	650
Mixed plastics	615	390
ELV-WEEE plastics (PP, ABS, PS)	610	395
PS	80	60

Table 1. Amounts of waste processed and output (recyclates) produced per polymer stream for mechanical recycling.
*These figures include only the PVC materials employed in the building and construction sector.

Plastic packaging

Rigid polyolefins

Within this group, PP and HDPE are mainly found. PP is widely recognised for its robustness and flexibility, making it ideal for various packaging applications. PP's high chemical resistance and ability to withstand varying temperatures make it a popular choice for food packaging and containers. Its flexibility allows for packaging solutions, catering to various consumer and industrial requirements. Typical applications of PP in rigid packaging include food containers, trays, lids for beverage bottles, personal care products, caps and closures.

HDPE is known for its strength and durability, which makes it suitable for packaging products that require a high degree of protection. HDPE's resistance to impact and moisture, as well as its low cost, make it an excellent material for containers, bottles, and rigid packaging solutions. Its recyclability also adds to its appeal as a sustainable packaging option. Some of the primary uses of HDPE are bottles (for detergent, milk and juice), containers, caps, closures, as well as tanks, drums and pipes.

Currently, between 85-90 % of the input waste of PP and HDPE mechanical recyclers comes from packaging. Of this packaging waste, 56 % comes from households, 28-29 % comes from commercial and industrial packaging, and 5-6 % comes from other sources.

Polyolefin films

The most common types of polyolefins (PO) used in film production are PP and different kinds of PE, like HDPE and low-density polyethylene (LDPE). These films are widely used in various applications due to their excellent properties, such as flexibility, moisture resistance, and chemical resistance. Polyolefin films are flexible and can be easily processed into different shapes and sizes. Consumer flexible packaging is extensively used in food packaging, shrink wrap, and protective films, for instance – for agriculture – due to their clarity, strength, and UV resistance. Currently, the primary source of PO films for recycling is commercial and industrial packaging, which makes up over 50 % of the incoming material, followed by household packaging (24 %) and other applications (e.g., agriculture, building and construction).

Figure 3. Different types of household rigid packaging.

Figure 4. PO films packaging employed in detergent (top) and food packaging (bottom).

Polystyrene (PS)

Polystyrene (PS), with its lightweight and insulating properties, is extensively used in packaging for food (e.g., cutlery, dishes, cups, tumblers, dairy containers), and other consumer goods. PS can be found in rigid forms, such as clear containers and trays, as well as flexible forms and foam packaging, i.e., EPS (expanded PS) which is used mainly for fish boxes and white goods, while XPS (extruded PS) is used mainly for trays. However, the latter is not considered further in this report due to lack of collection, sorting and recycling at scale. Plastic packaging (primarily dairy packaging, followed by commercial and industrial) accounts for more than 75 % of the incoming PS waste.[4]

PET bottles and trays

Polyethylene Terephthalate (PET) is highly valued for its clarity, strength, and barrier properties. PET is commonly used for beverage bottles and food containers due to its ability to preserve the freshness and integrity of the content. Bottles are often transparent and clear, although some are tinted green, light blue, dark blue, or are even opaque. Its recyclability further enhances its environmental appeal, making it a preferred choice for sustainable packaging solutions. PET bottles can be recycled effectively, with the potential to create new bottles using up to 100 % recycled material. PET trays are commonly used for food packaging in ready-to-eat meals, fresh produce, and dairy products. Despite being made from the same plastic, PET trays and bottles must be recycled separately due to their distinct properties. PET demand accounts for 7.1 % of the total European plastic demand, which is 3.5 Mt (PET fibres are not included).[5] In 2022, out of the 2.6 Mt of PET input waste streams to PET recyclers, 2.34 Mt were bottles, whereas 0.26 Mt were trays.[6]

Figure 5. Yoghurt cup made of PS.

Figure 6. Top to bottom: Bottles and a tray made of PET.

Waste Electrical and Electronic Equipment (WEEE) and End-of-Life Vehicles (ELV)

Waste Electrical and Electronic Equipment (WEEE) is a category that encompasses a wide variety of products, such as temperature exchange equipment, cathode-ray tube screens, flat panel displays, laptops, PCs, and small and large home appliances. On the other hand, End-of-Life Vehicles (ELV) refer to vehicles that have reached the end of their use. Unlike the different waste streams mentioned above, WEEE products and ELV are not entirely made of plastics. The amount of plastic contained in these stream types varies substantially based on the sub-stream considered. Vehicles, for instance, contain approximately 80 % of metals, while WEEE contain 40 to 75 %. However, both represent two key waste streams reported in the Circular Economy Action Plan (CEAP) while also being a significant source of plastic waste. Around 25 % by weight of WEEE consists of plastics in the form of several polymers, mainly Acrylonitrile Butadiene Styrene (ABS), PP, PS and Polycarbonate (PC)-ABS. In 2023, out of the estimated recycling input in WEEE and ELV facilities (750 Kt), ELV accounted for one-third, while WEEE accounted for the remaining two-thirds. Within WEEE, the categories of products, such as temperature exchange equipment (TEE) and small domestic appliances (SDA), represent the most significant share of processing and recycling.

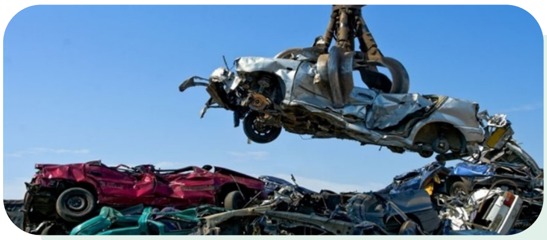
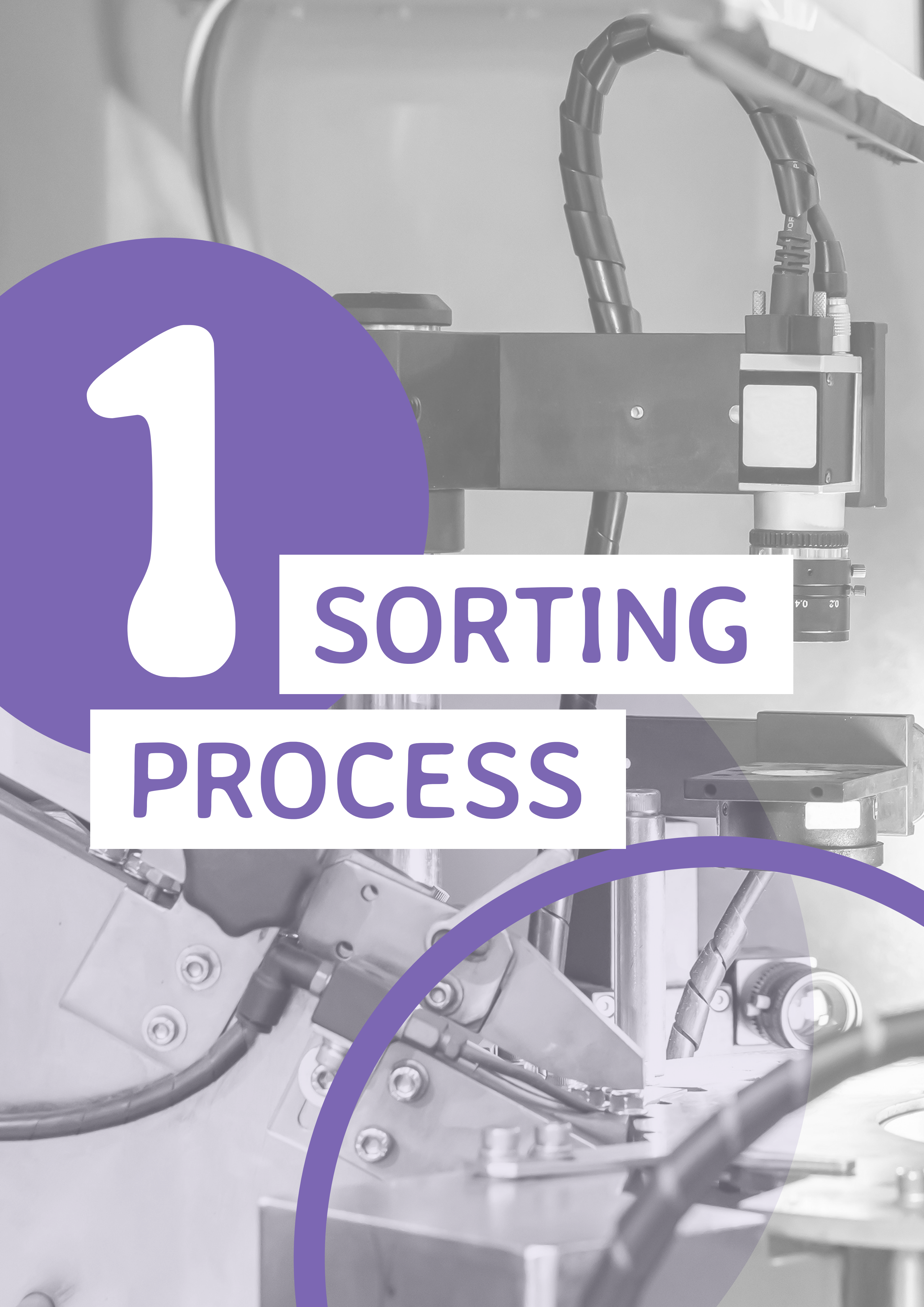


Figure 7. Top to bottom: mixed WEEE and car husks (ELV) at a collection centre.

Plastics for building and construction

Polyvinyl chloride (PVC) is mainly used in the building and construction sector. Other ‘minor’ applications of PVC include transportation, packaging, electrical and electronic, agriculture, and farming. PVC is either rigid or flexible, and used in products such as window profiles and sheets (rigid), foils (flexible), pipes, fittings and cables. According to figures collected by VinylPlus in 2024,[7] the highest share of recycling input material is represented by window profiles (50 %), while the rest is shared between flooring, cables, flexible PVC, pipes and fittings, and other rigids. Along with PVC, other polymers are employed in this sector. For instance, PE and PP have been used for pipes, while ABS is used mainly in industrial applications.

Figure 8. Top to bottom: close-up of a window profile and pipes made of PVC.



1

SORTING PROCESS

Sorting Modules

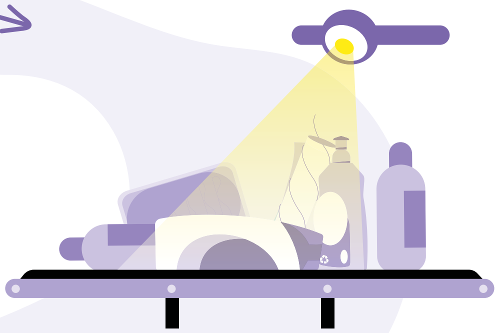
Before the recycling process begins, plastics undergo a sorting process. In all cases, three main phases (herewith ‘modules’) occur: collection, sorting and baling. Detailed information for each plastic waste stream can be found in the next sections.

1 COLLECTION

After a plastic product is used, it is collected with other plastics or mixed with metal or paper. Collection practices highly vary according to the type of plastic waste stream and Member State (MS) considered.

2 SORTING

Current technologies can sort the waste by material and product type. Thus, at this stage, plastic waste is separated from other material types. During the process, plastic waste is placed on a conveyor belt.



3 BALING/SIZE REDUCTION

The sorted plastics are compacted in bales that enter the recycling line for reprocessing in the following stages.

Sorting Technologies

In this section, the three basic modules illustrated beforehand will be elaborated, and specific differences in sorting technologies will be presented for the following plastics waste streams: packaging, WEEE & ELV, and building and construction.

Plastic Packaging Materials

Collection

Figure 9. Exemplary picture of the content of a plastic packaging bin in the city of Brussels (collection type: home separated).[8]

Generally, plastic packaging waste is collected at the household level and either 'home separated' (i.e., disposed of in a separate bin[9] by the consumer) or 'post-home separated', meaning collected by the consumer with the rest of the waste and then sent to materials recovery facilities (MRF). This step is sometimes complemented by further sorting at the plastics recovery facility (PRF). In some cases, specific collection systems, such as deposit return systems (DRS), are used — for example, for PET bottles.

Thus, the primary collection schemes are curbside collection, drop-off centres, and DRS.

Curbside collection is the most widely accessible collection method. Households place their plastic bottles and containers in designated containers or bins outside their homes. Then municipal waste management services or private waste collection companies collect the plastic waste directly from these containers on a scheduled basis.

Drop-off collection consists of containers for designated recyclable materials placed at central collection locations where residents can bring their plastic bottles and containers for disposal.

DRS programmes promote the collection and recycling of plastic bottles and containers by adding a small deposit fee on a product, which can be claimed back when the product is returned for recycling. This puts a value on used packaging and incentivises consumers to recycle. As such, DRS effectively achieves high separate collection rates and generates a clean stream for the recycling industry.

European institutions have recognised DRS as the most effective solution for achieving the ambitious target of the selective collection of plastic bottles. To support their implementation in the EU, the Packaging and Packaging Waste Regulation (PPWR) mandates that by 2029, MSs must ensure the separate collection of at least 90 % of single-use plastic bottles and metal beverage containers per annum. To achieve this target, they are required to establish DRS for these packaging formats.[10]

Compaction

After collection, packaging waste is transported to a sorting facility or recycling centre. This process also involves the compaction of plastic waste, which helps to optimise waste management processes by reducing volume, improving transportation efficiency, and facilitating recycling.

During the compaction process, especially in the case of mixed waste streams that include packaging materials, different packaging components can detach due to the mechanical pressure applied during compaction. Packaging containing components such as handles, closures, or decorative elements that are not attached to the packaging's main body can get separated during this step.

Figure 10. Exemplary picture of mixed plastic packaging arriving at the sorting centre, on a conveyor belt (top) and stacked (bottom).

Sorting

Sorting of packaging waste is an essential step for effective recycling. It helps maximise the amount of material that can be recycled, reducing contamination in the recycling stream and minimising the amount of waste sent to landfills or incinerators. Household waste consists of a large variety of plastics contaminated by a residual organic fraction and non-plastic materials like metal, aluminium or paper among others (see Figure 10). Proper sorting and cleaning of the incoming waste is necessary to generate high-quality recyclates through recycling.

Sorting can be performed manually or mechanically. In the first case, workers separate different types of packaging materials by handpicking. Today, in Europe, sorting facilities use mechanical sorting processes in which mechanical equipment can efficiently separate materials based on their size, shape, colour, and material composition. An exemplary flowchart for the plastic packaging sorting process is reported below in Figure 11.

Certain packaging features can lead to difficulties during the sorting process. According to RecyClass,[11] here are the main design incompatibilities for flexible and rigid packaging:

- **Size:** For flexible packaging, the size should not be smaller than 50 x 50 mm. Items smaller than this risk to be removed during sieving steps, meaning they may not be feedstock for recycling. RecyClass recommends a minimum surface area of 100 cm^2 to ensure effective sorting. For rigid packaging, the size should not be smaller than 50 mm after compaction.

- **Labels and Sleeves:** Large labels or full-body sleeves can result in incorrect sorting of rigid packaging. According to RecyClass for containers over 500 ml, labels or sleeves should cover less than 70 % of the surface. For containers 500 ml or smaller, coverage should be less than 50 %. Exceeding these limits can hinder the recognition of the underlying polymer during sorting, negatively impacting recyclability.

- **Material Composition:** Multi-layer structures can lead to problems during both sorting and recycling. These differing materials can confuse sorting technologies, particularly NIR detectors, leading to incorrect categorisation or rejection of the packaging. A mono-material approach is recommended to facilitate the sorting and the recyclability of the packaging.

- **Metallisation:** Metallised films and labels can obstruct NIR detection, leading to rejection of the packaging during sorting. Additionally, these components can increase the density of packaging materials, causing incorrect flotation separation or removal during eddy current separation processes.

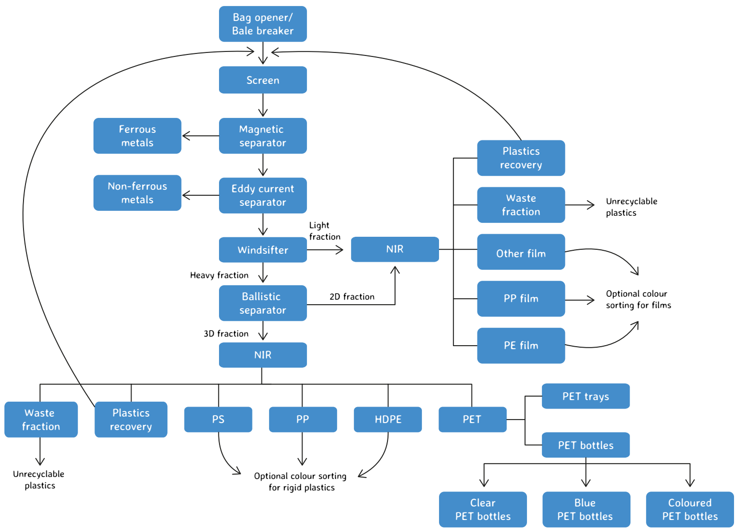
- **Colour:** Non-NIR detectable colours or large printing coverage can hinder the NIR sorting step. It is recommended to use natural or light colours.

- **Mixed Plastics:** Utilising different types of plastics, whether rigid and flexible combinations or varying materials on the front and back sides of packaging can lead to sorting and recyclability issues.

- **Shape:** Complex shapes, especially round forms made from very rigid and hard-to-compact materials, can impede the sorting process.

To support the industry and the recyclers, RecyClass has developed a standardised protocol that evaluates the sorting behaviour of plastic packaging at an industrial scale. It aims to recognise any design issues that may prevent the detectability of a specific product leading to it ending up in a different stream due to, for example, a large label or a sleeve which are made of a different polymer than the main body of the product.

A: Separation of Different Plastics Fractions by Sorting.



B: Sorting of PMD.

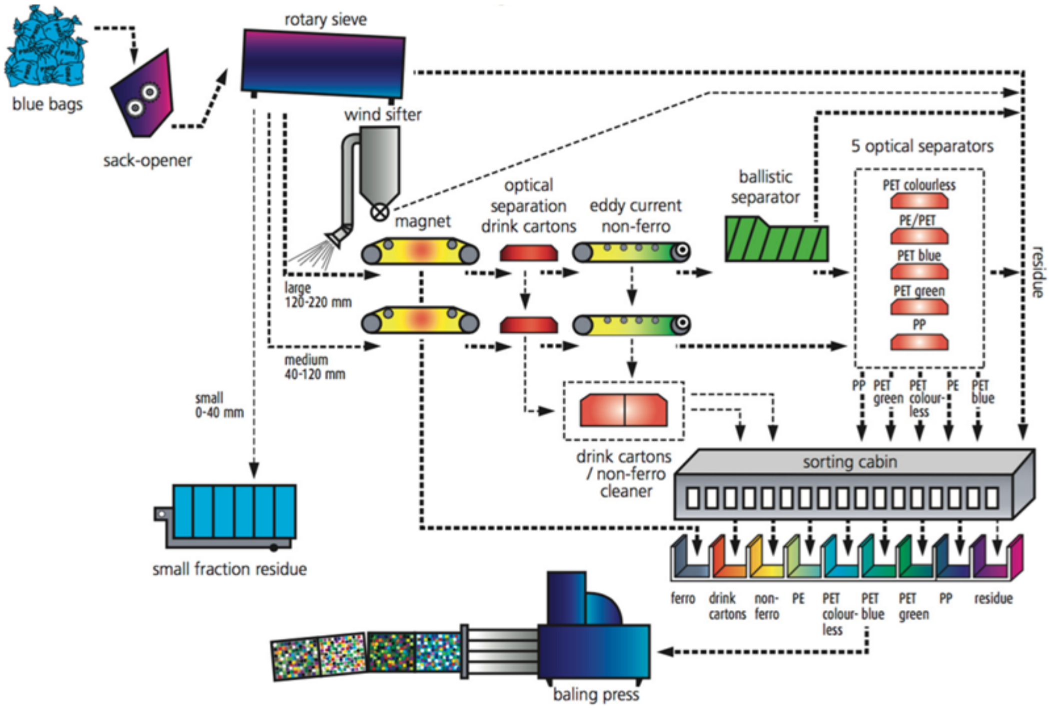


Figure 11. Exemplary sorting flowchart of (A) mixed plastics packaging waste and (B) mixed packaging waste (i.e., plastic, metallic and drinking cartons). Source: https://www.plasticsrecyclers.eu/wp-content/uploads/2022/10/pre-packaging-sorting-guidance-june-2019.pdf

Sieving

At sorting facilities, the received bales are opened utilising automatic bag breakers to efficiently sort household packaging. This process not only separates the contents of the bales but also aids in releasing any materials that may have adhered together during compaction in collection vehicles.

The household waste is then fed into a sieve with uniform openings of a specific size to classify the material into different sizes. The sieve is typically inclined at a certain angle and vibrates to facilitate the separation process. Another typical format is the “sieve drum”, which consists of cylindrical equipment with holes throughout its length. As the material passes through the sieve, particles smaller than the openings fall through the holes, while larger items remain on top and move forward to the next step within the sorting process. Some sorting facilities may have an additional sieve to further sort the undersized packaging. Usually, the first step consists of holes of 5 cm whilst additional sieves can be placed for elements between 2 and 5 cm. This process separates the packaging waste into different size fractions. Undersized packaging will end up in the residual fraction and most likely incinerated.

Windsifting

In the windsifting step, the plastic waste is passed through a system of air blowers and conveyor belts. These blowers generate a powerful stream of air that blows out or sucks lighter materials, such as plastic films, foils, bags and labels from rigid plastic containers. This machine utilises a fan to generate an airflow which can separate different types of plastics based on their weight and density. This allows for the separation of lighter plastic films from rigid plastics.

Magnetic separation

The magnetic separation step in the sorting plant helps to remove ferrous metals from the waste stream. The magnetic separator contains a powerful magnet that attracts ferrous materials, such as steel and, especially, plastic packaging containing metal components. If these are not removed from the packaging stream, they will highly pollute the output material. The plastic packaging containing metal material and the metals pulled out from the waste stream are collected and sent for further processing or recycling in a metal recycling plant.

Eddy current separation

The eddy current separator separates aluminium and other non-ferrous metals from the waste stream. This machine contains a rotating drum with powerful magnets inside. When an electric current is passed through the magnets, it creates a magnetic field that induces eddy currents in conductive materials, such as aluminium and other non-ferrous metals, generating a repelling force that causes non-ferrous metals to be removed from the waste stream.

During this step, the plastic packaging that contains aluminium layers will be removed from the stream and, therefore, will be lost.

Ballistic separator

The ballistic separation step helps to separate different types of materials based on their size and shape, allowing the separation between rigid and flexible packaging. The categorisation of packaging as either rigid or flexible is determined by the dimensions of the packaging, with rigid packaging being three-dimensional (3D) and flexible packaging being two-dimensional (2D). This step is crucial for packaging like pouches and tubes, which may fall into either the flexible or rigid category.

NIR technology

Following the previous steps, the material undergoes further refinement using near-infrared (NIR) technology. This technology separates the PE film from other films and plastics in the light and 2D fractions. The rigid plastics are then sorted into streams of PP, PE, PET, and PS.

Colour sorting

The material can be further sorted by colour (mainly for transparent and coloured) and product type. For example, PET bottles can be categorised by colour, as in clear, blue and coloured.

Baling

Production of bales

In the case of plastic packaging, most sorting centres produce bales directly after the sorting stage, which are then transported to recycling facilities (see Figure 12).

Figure 12. Exemplary picture of a pile of waste bales.

Waste Electrical and Electronic Equipment (WEEE) and End-of-Life Vehicles (ELV)

Figure 13 reports an exemplary flowchart of the WEEE and ELV collection and sorting processes, which constitute the steps prior to their recycling. These steps are thoroughly explained in the paragraph below.

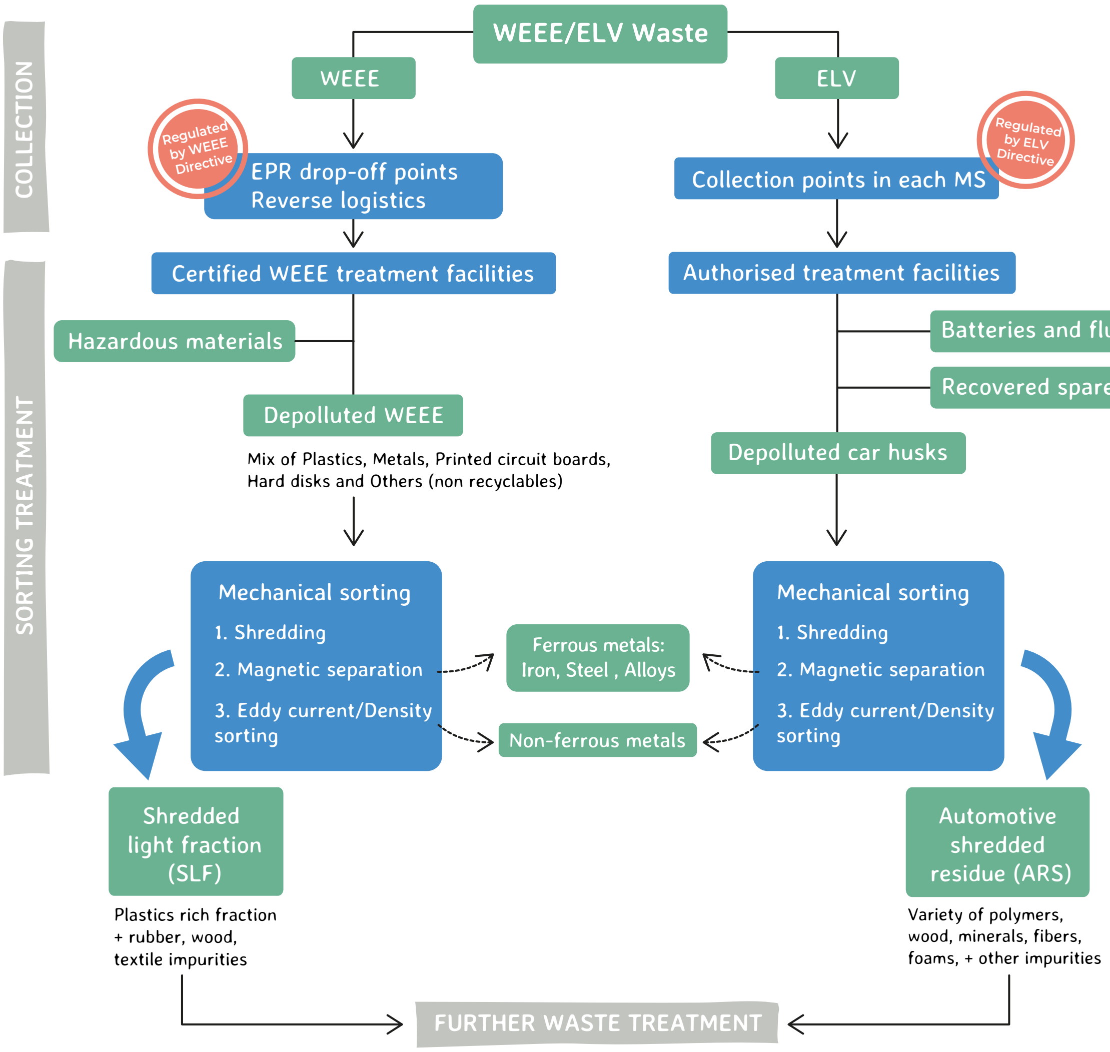


Figure 13. Exemplary collection and sorting process for WEEE (left) and ELV (right).

Collection

The Directive 2012/19/EU on WEEE[12] and the Directive 2000/53/EC on ELV[13] regulate the collection of the two waste streams. For both, waste is collected in specific collection centres, such as extended producer responsibility (EPR) organised drop-off points in case of WEEE, or official collection points in case of ELV.

Sorting

Treatment

The collected waste is sent to the respective treatment facilities, where the streams are treated to be separated from hazardous materials, and the different categories are separated by type (small IT equipment, fridge, small domestic appliances, etc.), to then be ready for the subsequent sorting steps. The treatment requirements for specific subclasses of WEEE (e.g. screens, small domestic equipment, large domestic equipment, and temperature exchange equipment) are defined by the annexes to the WEEE directive.[14] As for ELV, under the current ELV directive (ELVD), they must be treated in Authorised Treatment Facilities (ATFs), for which specific requirements apply and which must perform certain treatment steps as defined in the annexes of the ELVD (e.g. fluids need to be drained and lead acid batteries removed). In addition, ATFs tend to disassemble parts that may have a relevant economic value for reuse. The remaining husk is directed to specialised facilities that shred them. Then, in both cases (WEEE and ELV), the metals are removed. What is left after this is a plastic-rich fraction often indicated as 'shredder light fraction' (SLF) in the case of WEEE and 'automotive shredded residue' (ASR) in the case of ELV.[15] All the steps mentioned are further elaborated below.

Figure 14. Examples of different types of WEEE and ELV arriving at a specialised treatment facility. Top images: small IT equipment and home appliances, mixed appliances and printer, cables and other. Bottom image: ELVs.

De-pollution via dismantling

When sent to these specialised treatment centres, WEEE and ELV undergo the de-pollution required by the WEEE and ELV Directives and their national implementing legislation. For instance, cathode ray tubes containing highly hazardous substances are removed from TVs, as well as mercury from batteries and chlorofluorocarbon [CFC] from refrigerators. This step has the general aim of recovering the hazardous components and materials with economic value, and it is carried out through dismantling. The latter plays a crucial role in identifying potential resources in end-of-life (EOL) goods and preserving their technical and economic value.[16] However, the variations within the WEEE sub-streams bring about more difficulties in classifying and dismantling. Below, a list of the components recovered and discarded as waste from the main sub-streams of WEEE/ELV is reported.

SUB-STREAM	RECOVERED FRACTION (EXCLUDING PLASTICS)	WASTE FRACTION
Temperature-exchange equipment (e.g., fridges)	Glass trays, refrigerants	Blowing agents, liquid mercury, capacitors
Small and large domestic appliances	Cables, ink and toner cartage, paper, cardboard fraction, precious metals and copper	Hazardous components from batteries
CRT screens and flat panel displays, Small ICT equipment	Precious metals and copper	Hazardous components from batteries

Table 2. Non-exhaustive list of sub-streams from WEEE/ELV along with the respective recovered, sold and discarded fractions.

Three different types of dismantling procedures are reported and explained below:

Manual dismantling

Manual dismantling implies the use of hand tools and technologies to disassemble objects or equipment. Hence, it is carried out by professionally trained operators, whose role is to carefully check and identify each part of the disassembled objects and the relationship between them. Despite its high cost, as of today, the most common way to carry out the dismantling step is manually. Some sub-streams of WEEE, such as screens, are entirely dismantled by hand, while for others, there is a first manual step directly followed by shredding for metal recovery. All in all, this step allows the sorting of the entering WEEE into up to 20 different categories, and within these to recover some valuable components and remove the hazardous ones before the shredding operation.

Robotised dismantling

On the other hand of the spectrum, fully automated dismantling primarily utilises automated equipment and robot operations, with no or limited human involvement. Since manual dismantling implies direct human contact with the waste and high costs, new technologies are under development to limit this contact. Among these, robotised dismantling has been considered to replace the manual one, since it allows for saving energy while treating bigger amounts of material more quickly.[17] This technology is, however, still not implemented at the recycling facilities, while studies at the laboratory scale exist.[18]

Mechanical dismantling

As an alternative, some facilities have mechanical dismantling in place. Generally, the process consists of shredding, crushing, screening and separating the components mechanically and using heat. A sequence of different machines is usually in place to attempt discrimination of the different parts of the WEEE. For instance, printed circuit boards can be disassembled with this technology.[19] However, issues of fire safety might arise when employing heat (i.e., mechanical dismantling). Additionally, gas emissions and damage induced by overheating must be considered.

Size Reduction

Shredding and metals removal

After dismantling, shredding of WEEE/ELV into flakes is needed to separate metals from plastics and wood, increasing the efficiency of the subsequent sorting steps. For WEEE, the type of shredder used varies according to the sub-stream considered. Big appliances are often shredded employing hammer mill scrap shredders and crushers[20], while refrigerators can be treated with rotary shear and chain mill shredders.[21] Generally, the shredders operate in dry conditions, mainly because of the costs associated with wet grinding, i.e., water decontamination. During this step, over-band magnetic separators (low intensity) are initially employed to recover ferrous metals, while eddy current separation is used to obtain non-ferrous metals. Other separation techniques are used to produce other fractions (e.g., rubber separation).

As for ELV, the husk that remains after dismantling is directed to specialised facilities that shred it. In much the same way as for WEEE, magnetic separators recover ferrous metals, eddy current separators recover non-ferrous metals, and some other treatment steps are performed to recover other materials.

What remains at this point, for WEEE, is the 'shredder light fraction' (SLF), which contains various plastic materials and some impurities such as cables, metals, elastomers, rubbers, wood, stones, and fines (see Figure 15).

From ELV, what is left is the 'automotive shredder residue' (ASR), a fraction of material that likewise contains a variety of different polymers, plus some other impurities ranging from wood, glass, stones, cables, rubber, and more (Figure 15). On average, ASR tends to be slightly more complex in composition than SLF. Some recycling companies prefer to treat WEEE from TEE in a separate line from the beginning. This results in a 'cleaner' stream that enters the recycling line (see picture on the right in Figure 15).

Figure 15. Top to bottom: ASR from ELV, SLF from mixed WEEE and SLF from temperature exchange equipment. These are the fractions entering the recycling line (see Recycling technologies chapter).

Construction Materials (PVC)

In the case of plastic waste employed in the building and construction sectors, separate collection systems are in place, mainly involving an extended producer responsibility (EPR) scheme that deals with the collection of specific products.

Collection and sorting

As of today, there is no specific EU legislation or directive which regulates the collection of these materials. Thus, the latter is generally based on nationwide voluntary collection systems. In other cases, such as discarded PVC coming from minor applications (e.g., farming), there is no separate collection and recycling, and these fractions are considered as residual waste, often landfilled or sent to energy recovery (incineration). Below, some examples are reported for the collection of specific PVC wastes from building and construction, and a flowchart is provided in Figure 16.

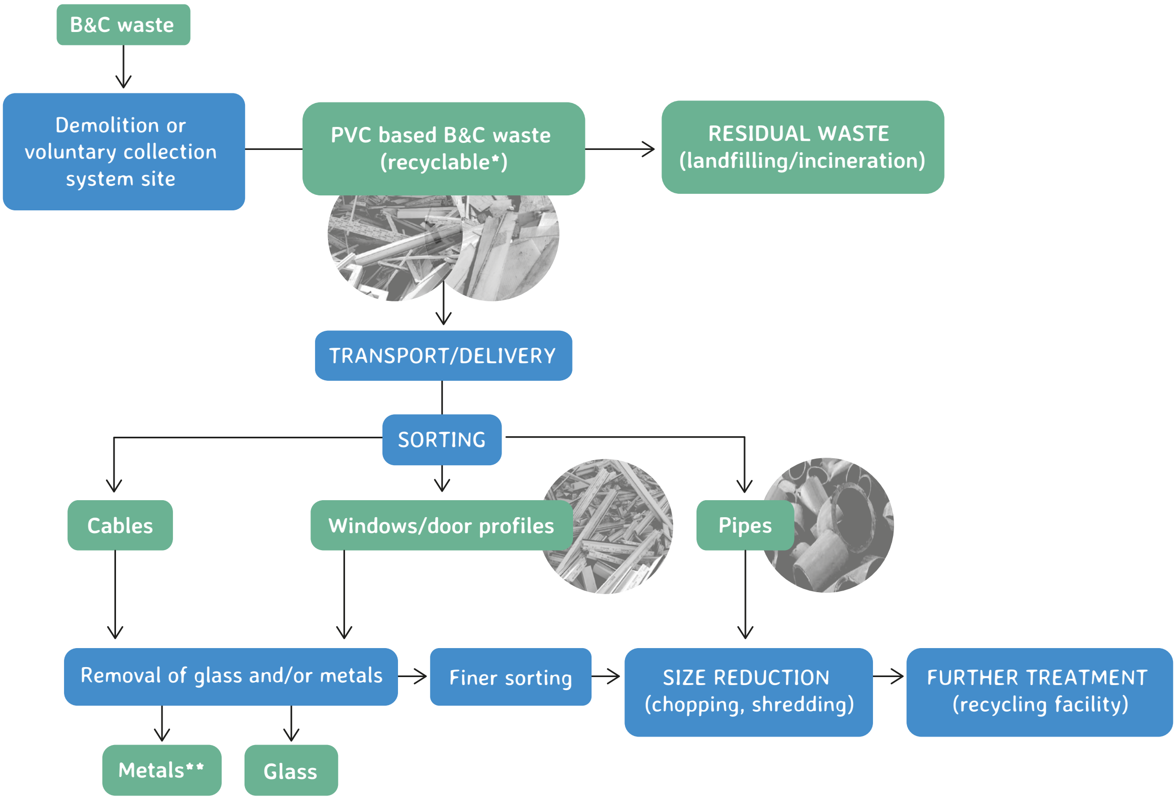


Figure 16. Exemplary flowchart of PVC sorting process from B&C waste. Please note that this process can follow a different sequence depending on country, region or demolition site.

Rigid PVC

In this case, the waste is mainly generated during construction (cut-offs), renovations, and demolition activities. Some examples of implemented collection systems can be found below:

- Customers of pipe manufacturers and profile hoses are actively encouraged to return cut-offs generated during construction activities.
- During large-scale renovations and demolition projects, profiles and above-ground pipe systems can be separately collected or collected along with other wastes. When collected along with other wastes, the mixed waste tends to go to specialised sorting centres where the profiles and pipes are sorted. The separately collected or sorted rigid PVC profile and pipe waste is directed to specialised recyclers that perform further processing.
- During smaller-scale renovations (and demolition projects), the same options exist as in the case of larger-scale renovations, but it is also possible for citizens to deposit the profiles and pipes at municipal drop-off points. In many Member States, there are specific containers at these points for the collection of "rigid plastics". In these rigid plastic containers, one would find PVC pipes and window profiles, but also other bulky rigid plastics. Specialised recyclers exist that sort and process this waste stream into valuable recyclates that cover the processing costs. These recyclers also recover the rigid PVC from this stream for use in new profiles and pipes.

Flexible PVC

The main post-consumer volumes are obtained from cables. Cables are recovered directly from buildings, infrastructure, and other sites mainly for their metal (primarily copper) content which has a very high value. Such cables are sent to specialised cable strippers and choppers that recover the metal from such cables and are left with cable sheeting. Such cable sheeting is typically moved in big bags in a ground state and will contain flexible PVC, crosslinked PE, (thermoplastic) polyurethane, rubber, textile, aluminium plastic composite film (shielding of, for example, ethernet cables), residual copper, and residual aluminium.

Size Reduction

Shredding and metal removal

After collection, the bulky waste (rigid PVC) is chopped into 1.5 m pieces (Figure 17). Generally, the material is subjected to a second shredding step to reduce its size and to separate it from other fractions such as steel and glass. Cables are treated as described above.

Figure 17. Sorted PVC waste: window profiles (left) and sheeting (right).

CONCLUSION

Efficient sorting is fundamental to advancing circularity in the plastics value chain, yet approaches vary widely across waste streams due to differences in material properties, collection systems, and regulatory frameworks.

Plastic packaging waste, usually collected via curbside systems, drop-off points, or deposit return schemes, presents high variability and contamination, especially when coming from the household collection. Mechanical sorting methods, such as sieving, ballistic separation, and NIR detection, enable polymer-specific separation but can be challenged by lack of design for recycling choices like multilayer films and non-detectable labels.

WEEE and ELV plastics require a multi-stage process involving depollution, dismantling, and shredding. While valuable metals are efficiently separated, the resulting plastic-rich fractions (e.g., SLF and ASR) are complex and contaminated, and as such, need to be further treated at specialised recyclers.

Construction and demolition plastics, particularly PVC, are managed through voluntary or EPR-based systems. Rigid PVC can be effectively recycled through take-back schemes, while flexible PVC, often from cable stripping, poses greater challenges due to mixed compositions.

Across all streams, sorting performance depends on upstream design, downstream infrastructure, and policy support. Harmonised design standards, binding collection targets, and investment in advanced sorting will be essential to improve recycling outcomes.

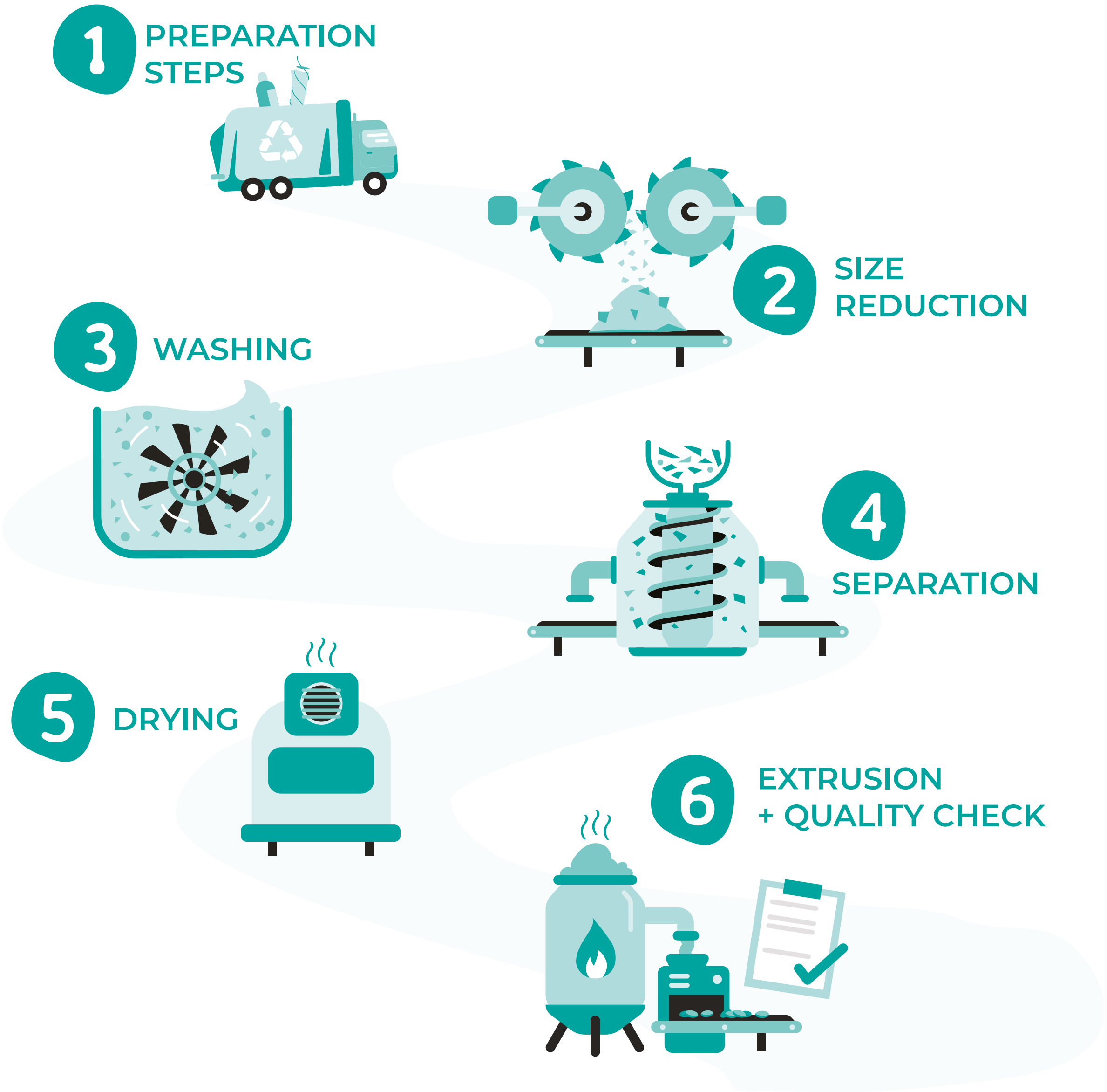
2

MECHANICAL RECYCLING PROCESS

Mechanical Recycling Modules

Mechanical recycling consists of a series of subsequent steps, hereafter referred to as ‘modules’, that are used for various materials, each with its own specific features. Below is a summary of these modules, categorised into *preparation steps, size reduction, washing, separation techniques, drying, and extrusion*.

While herewith a generic description of each is reported, specific details about the different waste streams are reported in the Recycling technologies chapter. It must be noted that not all units will be applicable to each stream presented in the next section.



Preparation Steps

Specialised recyclers might apply some preparatory steps before the process to ensure a smooth and efficient run of the line. For instance, some recyclers carry out further sorting before running the material through their line. These steps differ or are absent depending on the treated stream.

Size Reduction

What: The step often referred to as 'grinding' or 'shredding' reduces the plastics in flakes of a suitable size for recycling.

How: Grinding machines use rotating knives to break down both rigid and flexible plastics into flakes. The plastic is repeatedly cut until the flakes are small enough to pass through an adjustable screen filter, which determines their final size. The grinding process can be carried out under two conditions: wet or dry.

Wet grinding

The wet grinding process involves introducing water into the cutting chamber during the cutting process. The water flow serves to wash away dirt and contaminants while also stabilising the temperature within the chamber. By maintaining a consistent temperature, the water prevents the plastic from melting, which is essential for preserving the integrity of the flakes. Additionally, the cooling effect of the water helps to extend the lifespan of the cutting knives by reducing their wear.

Dry grinding

In a dry grinding process, no water is introduced into the cutting chamber, and the plastics are ground in a dry state. Without water, the knives can heat up sufficiently to melt the plastic within the cutting chamber. This melting can cause contaminants to become embedded in the plastic, making the machine more difficult to clean.

Washing

What: The washing step in recycling is a critical process used to clean the plastic flakes, removing any non-recyclable substances that could degrade the quality of the recycled material. This includes organic residues, labels, and other impurities.

How: The washing step usually involves a combination of water, sometimes heated up to 85 °C, and detergents or chemicals. There are two primary washing methods: cold washing and hot washing. As the names imply, the key difference between them lies in the temperature of the water used in the process.

Hot washing

Hot washing involves cleaning plastic flakes at temperatures exceeding 70 °C using caustic soda and detergents. This process effectively dissolves residues and removes contaminants. However, it is not utilised in all recycling lines due to its high energy consumption.

Cold washing

The cold washing process primarily employs water at room temperature, with or without the addition of detergent or caustic soda, to clean the flakes. This method is more cost-effective compared to hot washing.

Separation

Depending on the waste stream involved, distinct separation techniques may be applied, targeting the macro impurities (e.g., wood, foams, rubber) and metals or aiming at separating different plastic types and, in some cases, discriminating specific polymers. Below, a summary overview is provided, which will be further elaborated on in the stream-specific chapters.

Near-Infrared (NIR)

What: separation of different polymer types and plastic fractions.

How: Detection of the specific wavelengths of light that different types of plastics reflect when exposed to NIR light, which is a part of the electromagnetic spectrum just beyond the visible range (from about 780 nm to 2500 nm). Plastic waste is usually conveyed under a NIR scanner that emits near-infrared light onto the materials. Different plastics have unique chemical compositions, which cause them to absorb and reflect NIR light differently. The NIR sensor captures the reflected light, and a spectrometer analyses the wavelengths of this reflected light. The specific pattern of reflection (spectrum) allows the system to identify the type of plastic. Each type of plastic has a characteristic spectral fingerprint. Once identified, the system can use various mechanisms, such as air jets, to direct the identified plastic types into separate bins or streams for further processing or recycling. Some materials, especially black plastics, absorb NIR light and, therefore, cannot be detected accurately.

Density (sink/float technology)

What: separation of different plastic types, as well as macro impurities ('light fraction', consisting of wood, rubber and foams).

How: different plastic materials are separated depending on their density based on the sink/float principles. Each polymer is characterised by its own density, which allows its proper separation.

By suction

What: removal of macro and micro impurities such as rubber, foams and dust.

How: often, recycling lines are equipped with an in-locosuction system for the removal of dust (e.g. in the case of a post-consumer material) or rubber and foams (for instance, in the case of multi-material complex streams such as WEEE/ELV). The suction system runs across the line according to the specific recycling line.

Windsifting

What: removal of 'light' materials such as labels, paper and wood.

How: windsifting is a widely used technique in various recycling and processing lines. These systems employ an air knife with a blower to direct airflow through the material. This airflow causes a separation based on the difference in shape and size of the materials. Heavier materials are separated from lighter ones, with the lighter materials being blown further towards the discharge or extraction nozzle.

Magnetic separation

What: separation of ferrous and non-ferrous metals.

How: magnetic separators are widely used for the recovery of ferromagnetic metals from non-ferrous metals and other non-magnetic wastes from plastic waste streams.

Electrostatic

What: separation at the polymeric level.

How: electrostatic sorting allows further separation of different polymeric fractions based on their different conductivity. This method exploits the differences in the way various plastics acquire and retain electrical charges when exposed to an electrostatic field. The plastic waste is first shredded into small flakes or granules. After drying, the plastic flakes are charged via triboelectric or contact charging. The shredded plastics are often dried to remove moisture, as water can interfere with the electrostatic charging process. The charged plastic particles are then fed into the electrostatic separator, where they pass through an electric field created by electrodes with high voltage. The electric field causes the particles to move in different trajectories based on their charge-to-mass ratio. The deflected plastic particles are collected in separate bins or compartments based on their charge and type. This separation allows for the recovery of different plastic polymers that can then be processed for recycling.

By colour

What: separation of plastics characterised by different colours (e.g., white, natural, coloured).

How: the shredded plastic pieces are fed onto a conveyor belt, which moves them toward the colour sorting system. This employs optical sorting technologies that include: 1) Cameras and sensors: high-resolution cameras or advanced colour sensors scan the plastic pieces as they pass by on the conveyor belt. 2) Lighting systems: a controlled lighting environment ensures correct colour detection, for instance by using LEDs. The captured images or sensor data are processed by software algorithms. These algorithms analyse the colour information and classify the plastics based on predefined colour categories (e.g., clear, blue, green, white, etc.). Once a piece of plastic is identified by colour, an automated sorting mechanism is activated. This mechanism usually involves air jets or mechanical arms that divert the plastic into different collection bins based on its colour. For instance, if a piece of plastic is detected as blue, an air jet might blow it into a bin designated for blue plastics. Plastics with multiple colours or patterns, as well as black plastics, can be more challenging to sort accurately.

By other methods

Artificial intelligence (AI): Optionally, AI systems are implemented in recycling plants to generate data on key variables, which helps predict the overall composition of the feedstock and improve recycling processes. These systems can continuously monitor the composition of the feedstock by scanning the entire input and using object recognition to determine its makeup. AI can be tailored to meet a recycler's specific needs, with the ability to detect various polymers when combined with specific sensors or to sort materials into specific categories when paired with high-speed robots. These robots, receiving data from the AI, sort, pick, and place materials with speeds of up to 80 items per minute and an accuracy exceeding 95 %.[22]

Depending on the recycler's objectives and the type of material being processed, the analysis can focus on various aspects, such as the overall material composition, the ratio of food-grade to non-food-grade materials, or the reject rate to evaluate the proportion of recoverable items. The data generated allows for precise monitoring of the input material's composition. As quality requirements become stricter, AI plays a crucial role in increasing knowledge about the waste stream, particularly regarding composition and contamination.

Drying

Flakes are dried to get them ready for the extrusion process, as high moisture content can degrade the material as it is extruded.

Centrifugal dryer

What: centrifugal dryers remove excess water and some remaining contaminants from flakes.

How: the dryer uses centrifugal force, generated by a rapidly spinning rotor, to remove water from the plastic flakes.

Thermal dryer

What: thermal dryers reduce any residual moisture from the surface of plastic flakes by using hot air.

How: in the thermal dryer, the plastic material is exposed to hot air, which evaporates any residual moisture as the plastic flakes move through the system. Subsequently, the flakes typically pass through a cyclone separator, where any remaining moisture and fine particles are removed. This process also slightly cools the plastic to prevent overheating.

Extrusion & Quality Check

As a last step, flakes are molten and mixed during the extrusion process to obtain plastic pellets or granulates. This process includes degasification to remove volatiles and filtration to remove the finest impurities. It is carried out in a range of temperatures specific to the different materials to avoid polymer degradation.

Monitoring tools for substances in recyclates: PRE-1000

The resulting pellets are then checked to ensure that they meet the technical and regulatory standards.

To this aim, PRE developed the PRE-1000 voluntary industry standard to enable recyclers to verify compliance of recyclates with the applicable legislation on chemicals in a cost-effective manner. This method is meant to be integrated into the quality control procedure already present at recyclers' facilities. Recyclers are companies that purchase waste and place a product on the market. Thus, they need to ensure that this product is compliant with product regulation and that it fulfils the end-of-waste criteria of the Waste Framework Directive. Among others, the existing legislative and regulatory framework sets the following requirement on substances: a recycler that places a substance or mixture on the market as a product must inform its customer if there is a 'substance of very high concern' (SVHC)[23] present within the material above its regulatory cutoff value (often >0.1 %).

When preparing the PRE 1000 specification, PRE made an inventory of all Substances of Concern (SoC), including: all SVHCs, all substances under relevant REACH restrictions[24], all relevant persistent organic pollutants (POPs) substances and all the ones in the Restriction of Hazardous Substances (RoHS) Directive. At the moment, considering the evolving legislation and the consequent update of the standard, over 300 entries are listed. For each substance, PRE carried out an analysis to determine if the SoC can be present in plastics recyclates above the regulatory limit values by looking at several properties, spanning from physical-chemical properties and technical function to polymer specificity. The remaining substances that can be present within plastics, and thus plastic waste, typically contain certain elements that can be detected through handheld XRF devices that have a modest to high investment cost (e.g., 30,000 EUR) and a low marginal cost for each use (e.g., cents). While these devices cannot give an indication as to which molecule such elements are attached to, they can be used to calculate whether it is possible for a certain substance to be present above its regulatory limit value. Further chemical analyses are needed to quantify substances instead of elements.

The standard also suggests specific sampling protocols and sample preparation methods. During the PRIMUS project[25], it was determined that homogenisation of the material with granulation, followed by injection moulding, to produce plaques, plays a key role.

Mechanical Recycling Technologies

In this section, the modules mentioned in the previous chapter, such as *preparation steps, size reduction, washing, separation techniques, drying, and extrusion,* will be further elaborated according to the different types of plastic waste streams treated for recycling. For each stream, the basic modules have been kept and complemented by adding some sub-units when necessary to ensure the most complete level of detail. Specific recycling technologies are accompanied by the relative levels of implementation via the traffic lights system as explained beforehand (see introduction paragraph). The specific processes (e.g., recycling of rigid polyolefins, flexibles, WEEE/ELV plastics, etc.) are represented visually via exemplary schemes, which follow the legend below (a green box indicates the material, a yellow one a step that is optional in the process and the blue one a technology which is part of the standard process):

🟩 Material type 🟨 Optional step 🟦 Technology

Plastic Packaging

Rigid Polyolefins: HDPE and PP Rigid Stream

The recycling of rigid polyolefin (PO) materials follows a streamlined process focused on separating polymers and eliminating impurities. After grinding and washing, materials are sorted by density and weight, then dried and sifted. Near-infrared (NIR) technology is often used to distinguish between polypropylene and polyethylene before final colour sorting and extrusion into granules. The general recycling procedure for rigid polyolefins is schematically represented in Figure 18. While the recycling process may vary in some steps, highlighted in yellow in the Figure, the core of the process remains consistent for both PP and PE streams.

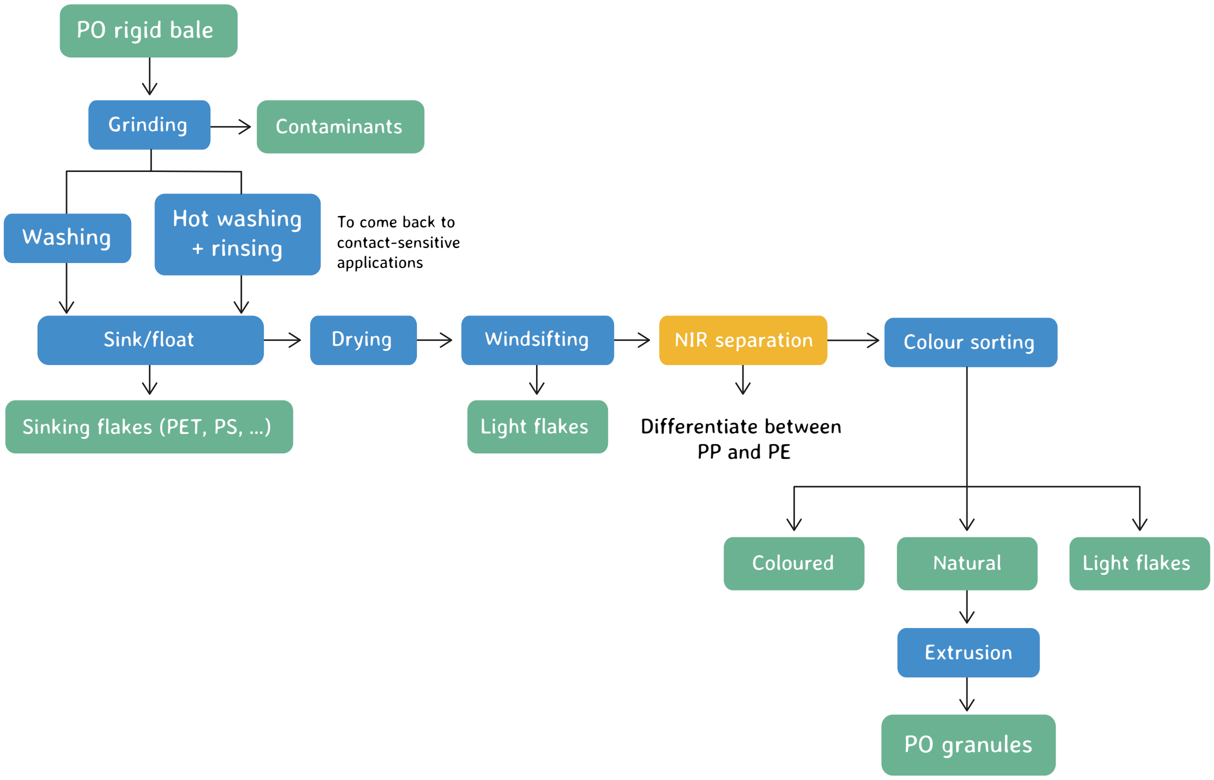


Figure 18. Schematic representation of the PO rigid packaging recycling process.

Preparation Steps

The recycling process starts by opening the pre-sorted bales (Figure 19) with a manual or automatic device. As an optional step, some recyclers in Europe perform an additional sorting step on the incoming material to sort out PS, PET and other contaminants and to divide the polymers according to their colour (natural, light colours, white and coloured).

Figure 19. From top to bottom: a stack of sorted bales of HDPE and PP, and in detail.

Size Reduction

The grinding step represents the very first step of the PO recycling process, and this is common to all recycling facilities. Most of the European PO recyclers use a wet-grinding process to remove contaminants and to shred the material. Typically, European recyclers use sieves between 10 and 20 mm at this stage.

Washing

The washing process for rigid POs is predominantly conducted under cold conditions, with most recyclers utilising room-temperature water without adding caustic soda or surfactants. An increasing number of recyclers are adopting mild washing (around 40 °C) or hot washing (approximately 80 °C) processes to produce recyclates suitable for contact-sensitive applications.

The resulting wastewater is typically treated internally by nearly all PO recyclers, who add flocculants to promote particle agglomeration and subsequent filtration. The filter mesh size among EU recyclers ranges from 100 to 2000 µm.

Figure 20. Washed PO flakes.

Separation

By density (sink/float separation)

The sink/float separation for the rigid PO stream is conducted using tap water, leveraging the fact that PO density is less than 1 g/cm^3. Consequently, the HDPE and polypropylene PP fractions, which have densities lower than tap water, float, while other fractions, such as PET and PS, sink. This process effectively removes PET sleeves that may be released during the washing step. However, the limitation of this method is the challenge of separating PP and PE fractions by density, as both have densities below 1 g/cm^3.

Windsifting

The windsifter uses an airflow to separate the light fraction, like labels, sleeves or small flakes, from the heavy fraction. Many recyclers perform this step, while a smaller percentage (ca. 30 %) proceed directly with the extrusion process.

By colour and polymer type

A colour sorting step might be conducted to separate flakes based on their colours. The PO recycling process categorises flakes into four fractions: natural, white, light-coloured, and coloured flakes. Additionally, some recyclers are incorporating a NIR separation step to remove non-PO materials and especially distinguish between PP and HDPE flakes, thereby preventing contamination during the extrusion process.

Drying

To remove excess water from the flakes, different types of dryers are used by the recyclers. Most PO recyclers use a centrifugal dryer, sometimes in combination with a thermal dryer. Rarely, a screw press dryer is used. The flakes are dried until they reach a moisture level below 3 %.

Extrusion

Flakes are extruded to obtain new recycled HDPE and PP pellets. The average extrusion temperature for HDPE flakes is set between 220 and 240 °C by most of the recyclers, few recyclers are using an average temperature higher than 260 °C. To filter out the remaining impurities, a mesh size typically used for HDPE is between 100 and 120 µm, while for PP it is between 100 and 250 µm.

PO Films Stream

The recycling of polyolefin (PO) films involves a structured process (Figure 21) designed to separate, clean, and recover usable polymer fractions. After the bales are opened and ground, materials undergo pre-sorting by type and colour, followed by washing (optionally de-inking), and drying. The process ensures the removal of contaminants and non-recyclable components, producing clean flakes suitable for extrusion. Below, the current and future technologies that apply to each recycling step are discussed, along with the rationale behind their use and a brief description of their output materials.

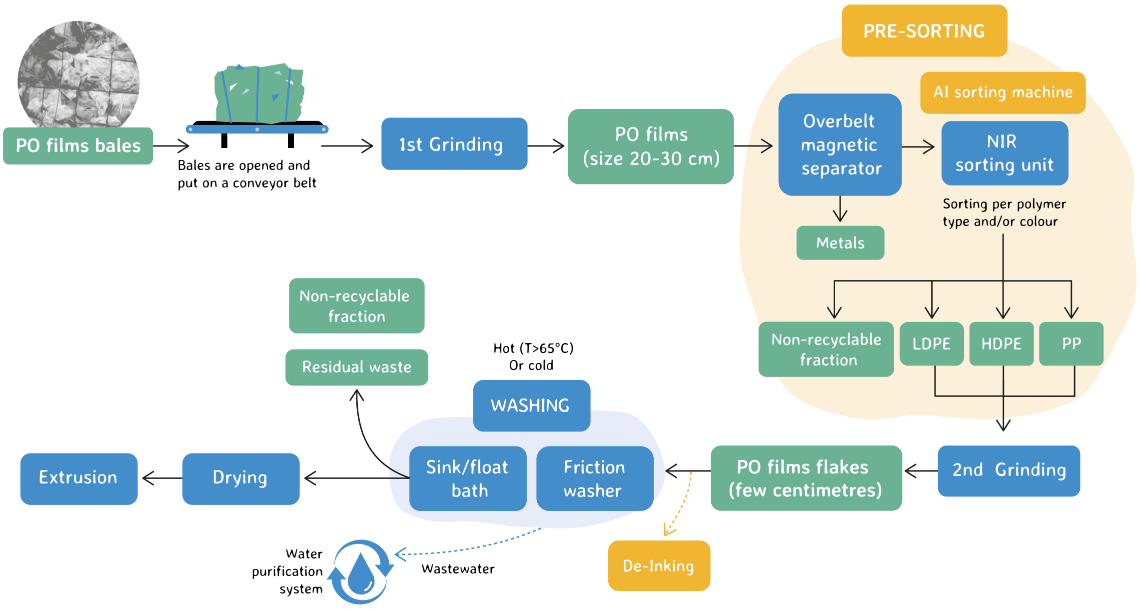


Figure 21. Exemplary flowchart of PO films recycling line, from bales to pellets.

Preparation Steps

Pre-sorting

From the sorting centre, sorted flexible films (e.g., foils, bags, wrappers, etc.) arrive at the recycling facility in the form of pressed bales. These bales can look quite different and have different levels of contamination (i.e., dirt, non-recyclable fraction) depending on the original material's application. Visual differences between household and agricultural[26] applications can be observed in Figure 22.

Despite being sorted at the sorting centre prior to reaching the recyclers, these materials often go through further sorting prior to entering the recycling line, which consists of the following units: grinding, magnetic separation, NIR sorting and optionally an AI sorting unit. Please note that the pre-sorting step is not always present and that, when it occurs, it is different according to the recycling line. Thus, not all the units mentioned above are necessarily implemented.

Grinding

A first grinding step allows to cut the materials down to 20-30 cm in size. An example of the fraction obtained after this step is reported in Figure 23. As one can notice, dirt, contaminants, and other material types (non-plastic) are still present after this stage.[27]

Over belt magnet

Magnetic separation is employed to remove cans and other metal-based contaminants, to further proceed with (almost) only the plastic fraction.

NIR

The flakes are then sorted out by, depending on the NIR sorting unit employed, polymer type (e.g., PE and PP) and/or colour (e.g., natural, white). For instance, in this stage, LDPE films are separated from other flexibles such as multilayers, black film, compostable films, metallised plastics and paper labels. Multilayers composed of incompatible materials are not recyclable and are discarded into waste streams.

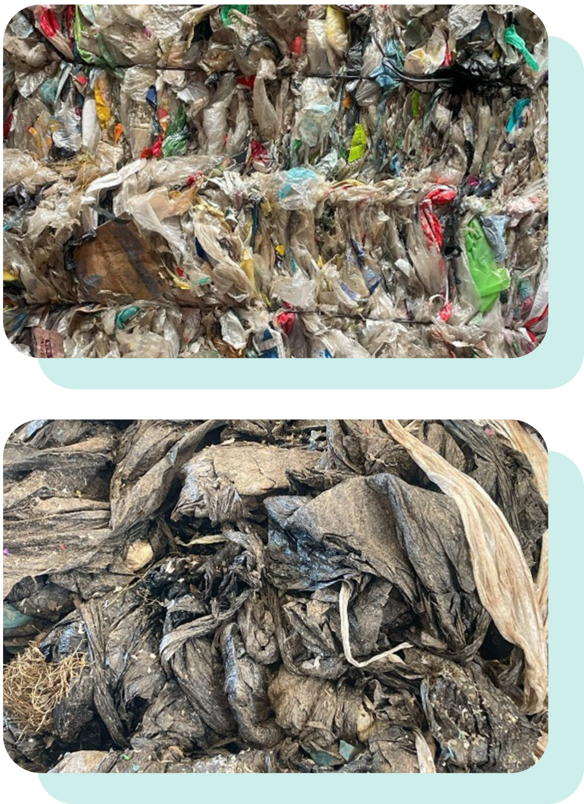


Figure 22. Waste bales of plastic film from household (top) and from agricultural applications (bottom).

Figure 23. Close-up of the PO films waste fraction after the first shredding.

AI sorting unit

An artificial intelligence-based sorting unit can be present to enable the sorting of different classes of materials present in the feedstock. Usually, a camera unit captures data, and this is then characterised by the AI model employed. Several material types can be detected quickly, such as flexibles, trays, composites and fabric.

Size Reduction

Grinding

The sorted flakes are fed into grinding machines that break them down into even smaller pieces or flakes (3-5 cm). This step makes the material easier to wash and process further. If the stream contains a significant fraction of organics, grinding can be paired with cold water to enhance the subsequent washing step.

Washing

Cold washing

The shredded PO flakes undergo a washing process to remove impurities such as dirt, labels, adhesives, and other contaminants. This may include cold or, more rarely, hot washing, often with the use of detergents and possibly caustic soda, depending on the level of contamination.

Friction washer

To remove contamination, flakes are washed using a friction washer. Figure 24 illustrates the washed flakes.

Figure 24. Flakes of PO films after the washing stage.

De-inking

Complementary to the regular washing process, de-inking is a process based on hot washing with the aid of chemicals (e.g., detergent in an alkaline aqueous solution). It targets specifically plastic waste films that are printed (e.g., packaging materials with branding, or coloured designs). At present, this step is optional with very little implementation at industrial scale, but it is foreseen to play a crucial role in the future washing process, especially for food-contact sensitive packaging applications.

Separation

Sink/float technology

The density separation step is built within the washing process. In a flotation tank, films float while heavier materials sink. Polyolefins, being lighter, tend to float, while denser materials sink. This step allows for further removal of the residual non-recyclable fraction that is left after all the previous steps.

Drying

Mechanical and thermal drying

The cleaned flakes go through a mechanical and thermal drying process to remove moisture. This is crucial to ensure the quality of the final recycled product. Screw press dryers are commonly used.

Extrusion

Single melt filter extruder

The dry flakes are melted and extruded into pellets. These pellets (Figure 25) are a form of recycled polyolefin that can be used as raw material for manufacturing new plastic products. For instance, LDPE pellets can be converted back into films, like collection and refuse bags, containing up to 100 % recyclates.

Figure 25. Pellets produced by the extrusion of PO film flakes.

PET Bottles Stream

The PET bottle recycling process involves a series of mechanical and chemical steps designed to recover high-quality PET granules from post-consumer bottles. The process begins with the sorting and removal of contaminants such as metals, labels, and non-PET materials, followed by washing, grinding, and advanced sorting techniques before the final extrusion and decontamination steps that yield reusable PET granules. Food contact recycled PET is employed for transparent clear/light blue and transparent coloured bottles, while non-food grade r-PET is used for coloured bottles. The process steps and technologies are further elaborated in the subsections below. Yellow boxes in the scheme below depict optional steps in the recycling process, such as decontamination, which is carried out only for food-grade r-PET.

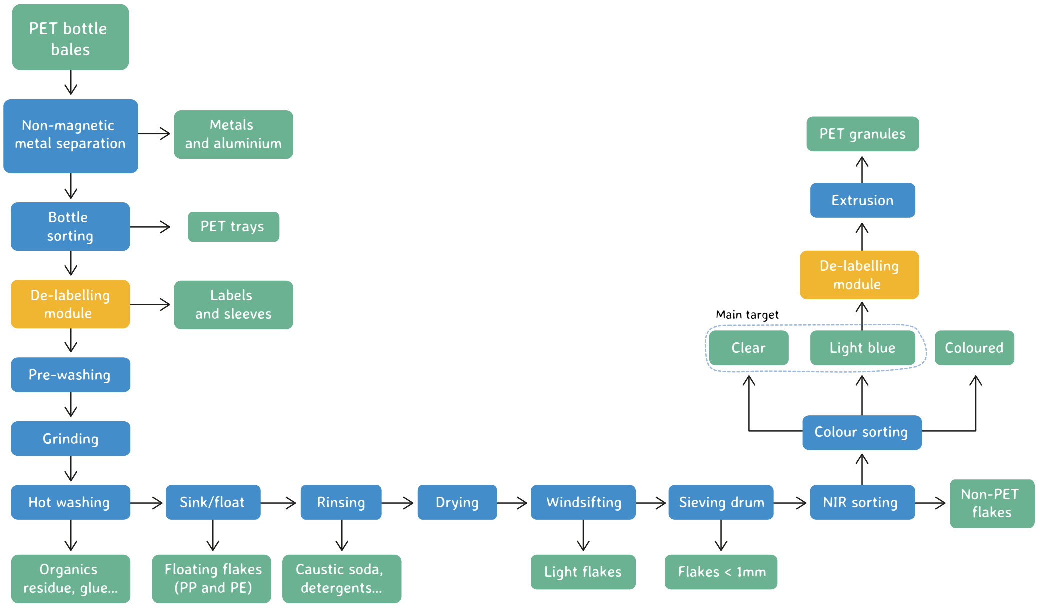


Figure 26. Exemplary flowchart of a PET bottles recycling line, from bales to pellets.

Preparation Steps

Pre-sorting

European PET bottle recyclers might perform a pre-sorting step on incoming bales to further purify the stream. The material is sorted by colour and type using NIR and camera systems. Dark or opaque bottles and trays are separated accordingly. Bottle sorting mainly targets transparent clear and transparent coloured bottles.

Figure 27. Detail of a PET bottles bale.

Magnetic and eddy current separation

Bale wire and potential metal contaminants, such as cans, are typically addressed in the first separation step of the recycling process. These materials can damage downstream equipment and are considered impurities in plastic recycling. To mitigate this, overbelt magnets and eddy current separators are used to effectively remove ferrous metals, aluminium cans, and composite materials such as Tetra Paks.

Artificial intelligence (AI)

A fraction of PET recyclers enhance their operations by integrating NIR modules with AI systems to identify all packaging entering the line or fine-tune a specific fraction.

De-labelling module

A label remover machine removes labels of PET bottles and is a key step to improve the purity of the rPET as the label material is often not made of PET, and it is complex to separate in the successive step. The PET bottles are fed via a belt conveyor into the de-labelling machine. Mechanical friction is causing a loss of the label. After that, a fan generates an airflow to separate and expel the labels from the line.[28]

Pre-washing

Some recyclers in Europe perform a first pre-wash to remove heavy material from the bottles and start cleaning the bottles as well as to start separating labels. The process uses a slow rotation speed for removing external impurities that are heavy and water-insoluble, like sand, dust, metal, stone, glass and others, such as labels. Then, through a conveyor chain system, the heavy contaminants are separated.

Size Reduction

Grinding

The bottles are shredded into small flakes, facilitating easier processing and further cleaning of the inside of the bottle. In Europe, recyclers typically use grinders with screen sizes ranging from 10 to 14 mm. Nearly all recyclers employ wet granulators for this process to prevent dust and use good friction washing.

Washing

Hot washing

European PET recyclers typically employ hot washing to clean the flakes, effectively removing labels, residual food contamination, and flavours. The standard conditions for this process include a bath temperature between 75 and 85 °C, the addition of approximately 0.2 to 0.8 % caustic soda, as well as a surfactant and anti-foaming agent with a concentration ranging from 0.1 to 1 %. The flake-to-water ratio is generally 1:3.

Figure 28. Detail of mixed PET flakes post washing.

Separation

By density

During this step, PP and PE labels and caps are separated, their density ensures they remain on the water surface, making it straightforward for rotating drums to move and separate them from the PET flakes collected by screw conveyors at the bottom of the tank. In contrast, PET labels or caps are more challenging to separate due to their similar density to PET flakes. If not adequately removed, they can deteriorate the quality of the final recyclates by introducing materials with different melt flow indices and properties. By standardising the use of PP or PE labels and caps, which do not contain fillers that can change the density of the caps above 1 g/cm^3, recyclers can streamline the separation process. This helps reduce contamination and results in higher-quality recycled PET.

Rinsing

To ensure the cleanliness of the flakes coming from the hot washing zone of the PET flakes, they pass through a rinsing module full of water at room temperature. During this process, the remains of detergent and small contaminants are removed. This module contains centrifuges for dewatering and filtering, as well as removing caustic soda and detergents.

Drying

In PET recycling lines, the flakes are typically dried using centrifugal drying machines, sometimes in combination with thermal dryers, to achieve a moisture level usually below 1 % by weight. In some European countries, for flakes to be considered End-of-Waste according to UNI 10667, the moisture level must be under 0.8 %.

Windsifting

This step further purifies the PET flakes by using air to separate lighter contaminants, especially PET fines, from the heavier PET bottle flakes.

Sieving step

Following the air separation process, an additional size classification step is employed using a sieve. This ensures that any remaining small flakes, usually below 1 mm, are effectively removed.

NIR & Colour Sorting

Flakes are sorted by colour and polymer type to remove any remaining non-PET polymers and to differentiate between coloured, light-coloured, white, and natural flakes. This step occurs after the flakes are dried.

Figure 29. Left to right: sorted blue, brown and light blue PET flakes

Extra Step

Decontamination

To ensure rPET is suitable for food contact applications, it must meet specific requirements set by Regulation (EU) No 2022/1616 and the European Food Safety Authority (EFSA).[29] The PET flakes used must be derived from separately collected post-consumer PET containers, with no more than 5 % originating from non-food consumer applications. These flakes undergo a hot caustic wash and drying process to remove surface contaminants. Intensive decontamination is required to bring the flakes to a food-grade approval level. The decontamination is carried out using critical parameters, including high temperature, duration, and vacuum or nitrogen gas flow. This process can be applied to the flakes, the melted flakes, or the granules derived from the flakes. These critical parameters effectively remove volatile contaminants making it suitable for food contact.

Extrusion

PET material is typically extruded at temperatures between 275 and 290 °C using a single screw extruder. Additives are rarely added by recyclers, while chain extenders are occasionally used. The mesh size of the filters used during extrusion generally ranges from 50 to 100 microns, with 50 microns being the most commonly used size.

Figure 30. Left: Crystallised PET flakes, right: Amorphous PET flakes

PET Trays Stream

The recycling of PET trays follows a process adapted to their specific material properties and structure. Mono-layer PET trays composed primarily of a single PET material, are generally compatible with conventional recycling processes and can be more readily reprocessed into high-quality recycled PET products. The recycling process for mono-layer PET trays includes metal separation, sorting by polymer type and food-grade status, thorough washing, and decontamination to ensure compliance with food-contact standards and to maintain material quality. A detailed explanation of the recycling steps associated with the mono PET tray stream is provided below (Figure 31).

Multi-layer PET trays, which often incorporate functional barrier layers or a polyethylene sheet, require more advanced treatment. While the initial preparation steps are similar to those used for mono-layer trays, the key difference lies in the washing stage, which focuses on delamination. This process typically involves hot washing or solvent-based methods to separate the PET layer from the PE or other non-PET components. After delamination, the PE is recovered and recycled via a separate stream, while the PET is further purified and reprocessed. Emerging technologies and pilot-scale implementations have demonstrated that, with effective separation, multi-layer PET trays can also be recycled into high-purity rPET suitable for demanding applications, including food-contact uses.

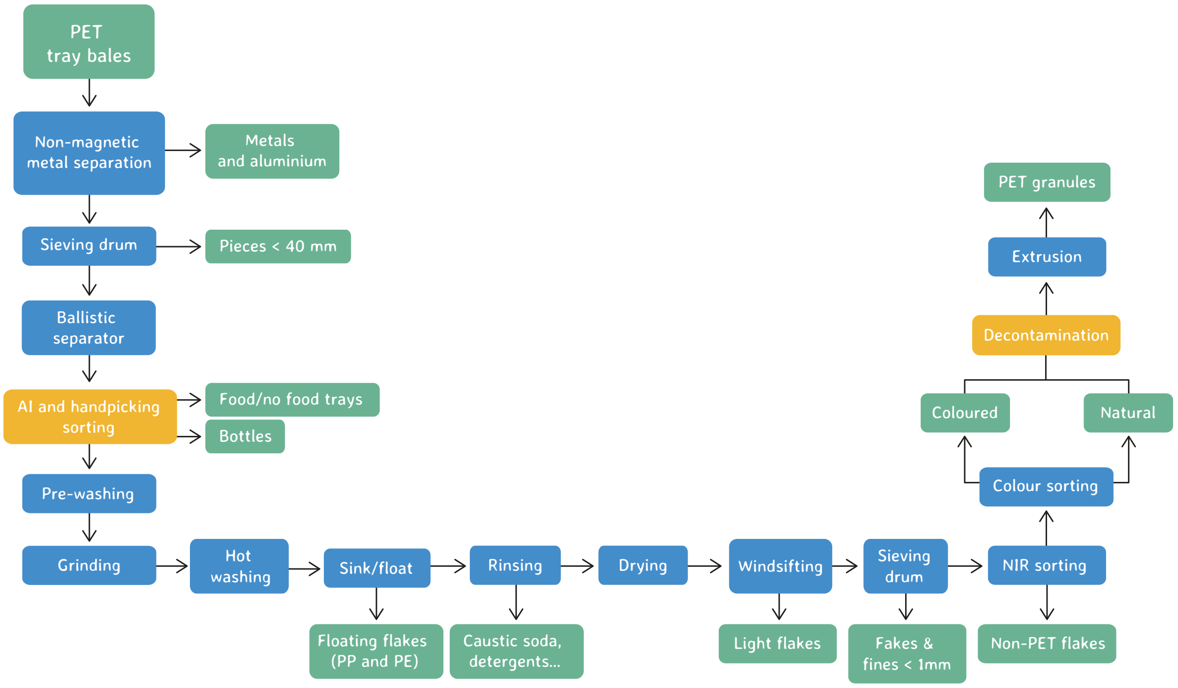


Figure 31. Exemplary flowchart of a PET tray recycling line, from bales to pellets.

Preparation Steps

Metal separation

Bale wire and potential metal contaminants, such as cans, are typically addressed in the first separation step of the recycling process. These materials can damage downstream equipment and are considered impurities in plastic recycling. To mitigate this, overbelt magnets and eddy current separators are used to effectively remove ferrous metals, aluminium cans, and composite materials such as Tetra Paks.

Ballistic separator

This process typically targets the removal of lightweight, flexible contaminants such as plastic films, shrink wraps, shopping bags, and other similar materials, which often accompany post-consumer PET packaging waste.

Sieving drum

Small pieces are removed using a rotating sieving drum with holes typically 40 mm in diameter, which prevents smaller fragments from continuing through the process.

Pre-sorting

PET tray recyclers typically perform a pre-sorting step on incoming materials (Figure 32). During this process, the input material is separated into food-grade and non-food-grade categories, as well as between PET bottles and PET trays. Trays made from materials other than PET are then identified and sorted using AI and manual picking.

Additionally, metals and aluminium, which can often become trapped in trays during the compaction process in the collection phase, are separated using magnetic and eddy current separation techniques.

Pre-washing

As trays are very thin and lack a protected interior surface, they tend to accumulate a significant amount of external contamination. Pre-washing is essential to remove this contamination. As indicated in the flow diagram, this process is part of one of the multiple water circuits used to achieve a high level of cleaning. The treatment and maintenance of these water circuits are crucial to ensure consistent operation and optimize water usage.

Figure 32. Stacked bales of PET trays.

Size Reduction

Grinding

The trays are reduced to small flakes through a wet grinding process, utilising screens with an approximate size of 12 mm. Due to the rigidity of the material, fines are often generated in this part of the process.

Washing

Hot washing

After grinding, the PET flakes undergo a prewashing step followed by a hot wash at approximately 70 ± 5 °C. During this stage, contaminants, food residues, and odours are effectively removed from the flakes. Labels and adhesives are also separated from the flakes.

PP and PE labels are preferred for recycling because they can be easily separated during the subsequent flotation step once detached. This helps ensure a cleaner and more efficient recycling process.

Figure 33. Picture of mixed PET flakes post-washing.

Separation

By density

The PP and PE fractions are separated from the PET flakes, which sink to the bottom of the tank and are introduced to the subsequent steps of the recycling process.

Windsifting

In this step, rigid PET flakes are separated from lighter flakes, such as those from labels and fines generated during the process, using air blowing.

Sieving step

To remove fines, an additional size classification step is employed. This ensures that any remaining small particles (fines) are effectively screened out, preventing them from entering the NIR and colour sorters.

Flake sorting

Flakes are sorted by colour and polymer type to remove any remaining non-PET polymers and to differentiate mainly between coloured and natural flakes.

Drying

Centrifugal drying

Pellets are dried using a centrifugal dryer until they reach a suitable moisture level lower than 1-1.5 % before being decontaminated and extruded.

Decontamination

To ensure PET is suitable for food contact applications, it must meet specific requirements set by the EFSA. The PET flakes used must be derived from post-consumer PET containers, with no more than 5 % originating from non-food consumer applications. These flakes undergo a hot caustic wash and drying process to remove surface contaminants. Intensive decontamination is required to bring the flakes to a food-grade approval level. The decontamination is carried out using critical parameters, including high temperature, duration, and vacuum or nitrogen gas flow. This process can be applied to the flakes, the melted flakes, or the granules derived from the flakes. These critical parameters effectively remove volatile contaminants and, in most cases, improve the polymer's molecular weight, making it suitable for food contact while preserving its original mechanical properties.

Extrusion

The PET flakes are extruded into pellets at a temperature typically around 275-285 °C, using a mesh size between 40 and 100 µm.

PS Stream

As mentioned above, when it comes to PS materials, a split exists between rigid and foamed. Given the fact that XPS are not collected, sorted and recycled at scale and that EPS has limited applications (fish boxes and white goods), they are not in the scope of this report. The recycling process that exists at industrial scale for polystyrene (PS) focuses on recovering rigid and semi-rigid packaging materials, such as yoghurt pots and trays. After pre-sorting and removal of non-PS items, the material is ground, washed, and separated by density. Further sorting by colour and weight ensures a clean PS flake stream, which is then dried and extruded into pellets for reuse.

Figure 34 portrays the entire recycling process to which PS waste is usually subjected, illustrating the different steps and their output materials. Below, the current and future technologies that apply to each step are discussed, along with the rationale behind their use and a brief description of their output materials.

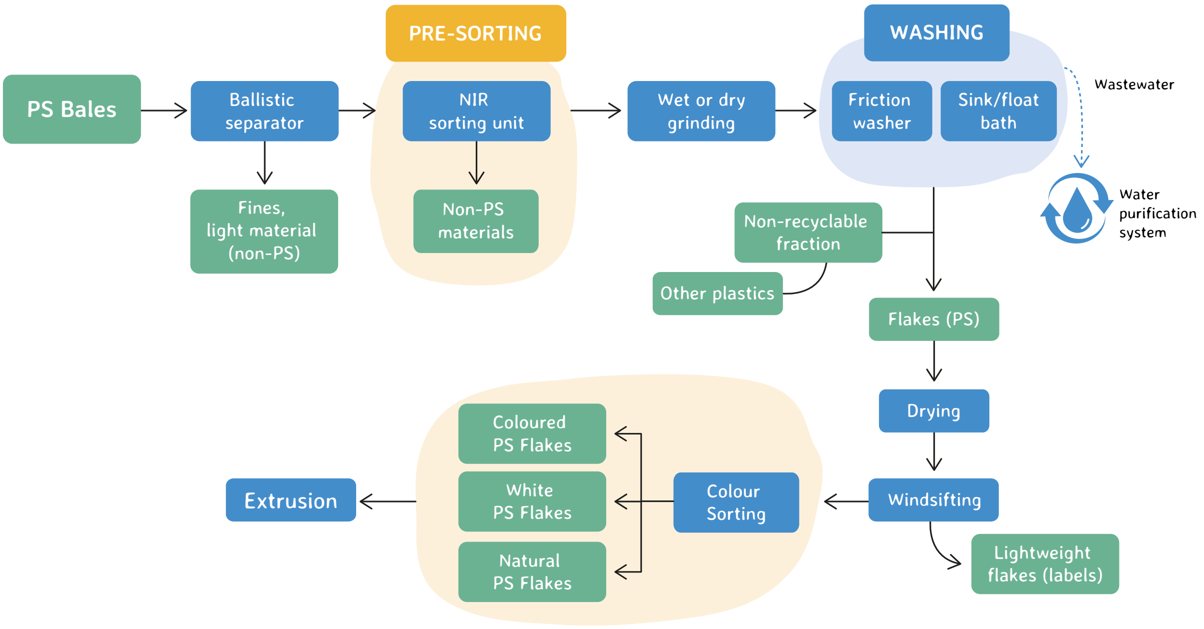


Figure 34. Exemplary flowchart of a PS recycling line, from bales to pellets.

Preparation Steps

Pre-sorting

With the first sorting step done at sorting centres, the waste bales contain mainly PS articles. Over 70 % are yoghurt pots, while the rest are trays and non-PS materials. For this reason, a pre-sorting is usually carried out at the recycling facility so that the final stream is mainly rigid PS. In addition, expanded PS is sorted out from the input stream. So, primarily rigid and semi-rigid PS are used as input materials for the recycling process.

NIR

The PS waste is fed onto ballistic separators (or sieve drums) that remove the fines from the rest of the waste, which is spread on a transport belt, where metals and the remaining non-PS-containing articles (such as PET, polyolefins, etc.) are sorted out by standard NIR technology. Usually, these materials amount to ca. 5 % of the input waste (i.e., the pre-sorted PS bales).

Figure 35. Bales of PS packaging waste.

AI sorting unit

Occasionally, the obtained PS stream is further sorted, and any non-food packaging articles are removed by either object recognition-based artificial intelligence or humans. This sorting step removes PS materials such as CD-ROM packaging, flowerpots, clothes hangers, cosmetic packaging, etc.

Size Reduction

Grinding

The sorted PS stream is then sent to the shredder, which reduces the size of the articles to flakes of about 1 cm^2. Most PS recyclers employ dry grinding, but some carry out this step in wet conditions.

Washing

Pre-washing

The washing step comprises pre-washing via friction washers and then separation that occurs in the sink/float step (see next section), where more than one tank can be used to separate the PS flakes from other remaining plastic fractions.

Figure 36. Detail of washed PS flakes.

Separation

Sink/float technology

While in the washing bath, PS flakes are separated from other plastic fractions according to their density. Usually, a first separation step is carried out at 1 g/cm^3 and a second at 1.08 g/cm^3. In this way, the fraction comprising incompatible materials with different densities (PVC, PET, aluminium foils and PO) that might still be present is furtherly separated from the PS.

Colour sorting

The washed and dried PS flakes are then introduced into the colour sorting process using NIR technology, resulting in a natural and coloured fraction of PS flakes.

Drying

Centrifugal

After the washing step, the flakes are dried, mainly with a centrifugal drying process, to bring the water level down to 0-3 %.

Windsifting

Once dried, lighter flakes (for instance, deriving from labels and lids) are separated from the rigid fraction.

Extrusion

Finally, the flakes are extruded into pellets at a temperature range of 220-230 °C. The mesh size of the filters employed varies from 90 to 200 μm.

Figure 37. Detail of PS extruded pellets.

Food Contact Recyclates

Over the past decade, the plastics recycling industry has developed a range of new processes and technologies for recycling plastics intended to be used in contact with foods. These advancements outpaced the limited scope of Regulation (EC) No 282/2008, eventually making it impossible to approve new processes, as they fell outside the framework's ability to assess their safety. Regulation (EU) No 2022/1616, on recycled plastics intended to come into contact with foods, provides a framework for the development of 'novel technologies' being technologies that have not yet been evaluated by the European Food Safety Agency (EFSA). To this end, many developments are currently ongoing to produce food-grade mechanically recycled plastics, especially ahead of the targets introduced in the Packaging and Packaging Waste Regulation.

Waste Electrical and Electronic Equipment (WEEE) and End-of-Life Vehicles (ELV)

For WEEE and ELV plastics, the recycling process is held in specialised recycling facilities, where a series of steps take place to remove the non-polymeric impurities and separate the plastics by polymer type. The input of specialised WEEE and ELV plastics recyclers is the shredder light fraction (SLF) and/or the Automotive shredder residue (ASR). This fraction of material, obtained at WEEE and ELV treatment centres, contains a variety of polymers, together with impurities such as paper, metals, wood, textile and other material types. A visual representation of SLF from mixed WEEE and TEE, as well as ASR, is given in Figure 38. The recycling process includes dedicated steps and technologies to obtain homogeneous plastic fractions with a low additive content.

Figure 39 reports the entire recycling process to which the WEEE and ELV waste is usually subjected, illustrating the different processing steps and their output materials. Below, the current and emerging technologies that apply to each recycling step are discussed, along with the rationale behind their use and a brief description of their output materials.

Figure 38. Examples of shredded fractions that make up the input of specialised WEEE and ELV recyclers.

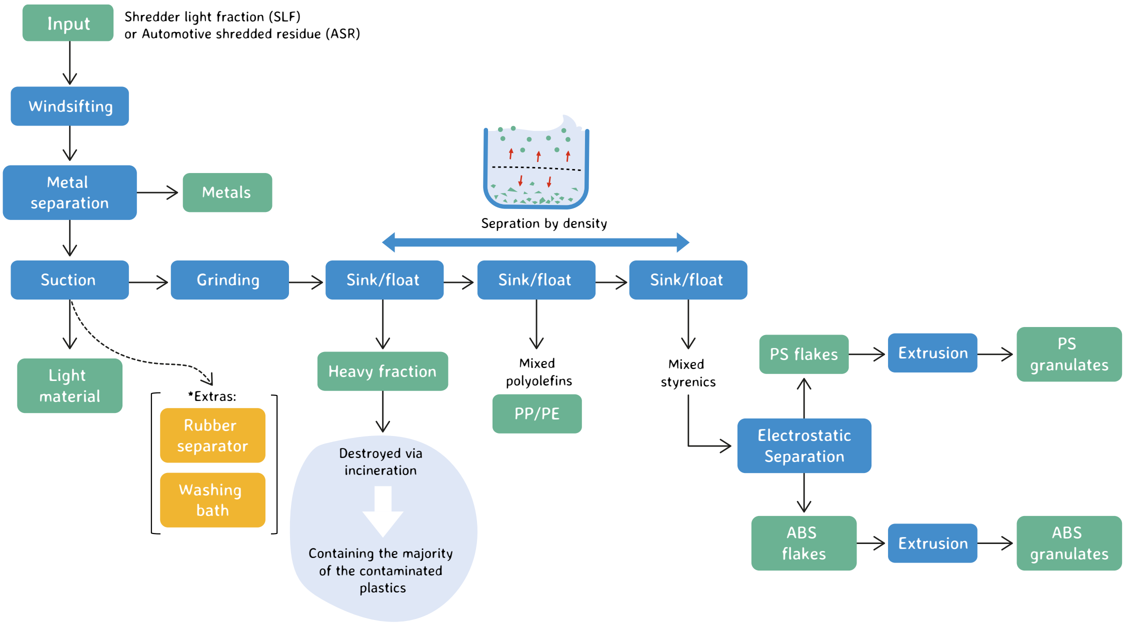


Figure 39. Schematic representation of a recycling process for WEEE and ELV materials.

Size Reduction

The mixed plastics fraction is shredded to be reduced in size and optimise the subsequent processes. The shredding of WEEE into small particles allows the liberation of metals from plastics and wood. Some separation steps, such as the ones described below, often happen simultaneously with the shredding step.

Separation

During the recycling of WEEE and ELV, several separation techniques are applied at different levels: firstly, non-polymeric macro impurities are removed, and then the remaining fraction (mainly plastics) is treated to remove contaminants. Finally, polymers are separated by type via further treatments.

Removal of Non-Polymeric Impurities

Firstly, the mixed plastic-rich fraction undergoes a preparation step where it is cleaned from non-polymeric impurities (e.g., metals, paper and other light materials), via the following methods and technologies:

Windsifting

This step allows for the separation of materials regarded as 'light fraction', such as paper and labels.

Suction

Employed for the separation of light material, such as foams. Suction systems run through different areas of the recycling line.

Washing bath

A water bath is employed to remove macro-impurities such as dirt, fines and mineral residues.

Rubber separator

Specific separators might be present in this recycling line. In the case of rubbers, these are macro-impurities which are removed via tailored rubber separators.

Magnetic sorting

Overbelt magnetic separator:

Overbelt magnet systems are used to separate metals on conveyor belts. The magnet system removes ferrous particles from the passing flow of materials. After leaving the magnetic sector, these iron particles are dropped into a receptacle.[30]

Non-ferrous separators (eddy current)

Eddy current separation allows the recovery of non-ferrous metals. This system is based on the use of rare-earth permanent magnets.[31] They usually consist of a conveyor system with a rapidly revolving magnetic rotor, able to generate an induction field through magnetic poles.

Removal of Contaminated Plastics and Polymer Separation

Sink/float technology

Density-based separation processes are, in this case, carried out via three baths, characterised by three different densities, to separate: a polyolefin fraction (<1.0 g/cm^3), a styrenics fraction (1.0 – 1.1 g/cm^3) and a residual waste fraction (>1.1 g/cm^3). For instance, the plastics containing functional levels of flame retardants (FRs) will be separated into the residual waste fraction as functional levels of flame retardants increase the density of the plastic flakes to >1.1 g/cm^3. According to the POPs regulation, after being separated, this fraction must be destroyed, thus sent to incineration. However, this technique will not work properly when targeting plastics in the same range of densities (e.g. PC-ABS, PS, ABS). The scheme below illustrates the general process of separating plastic flakes having different densities via the sink/float technology that can be found in WEEE/ELV (Figure 40). Figure 41 depicts the typical plastic fraction left after the first density bath, i.e., the decontaminated shredded fraction.

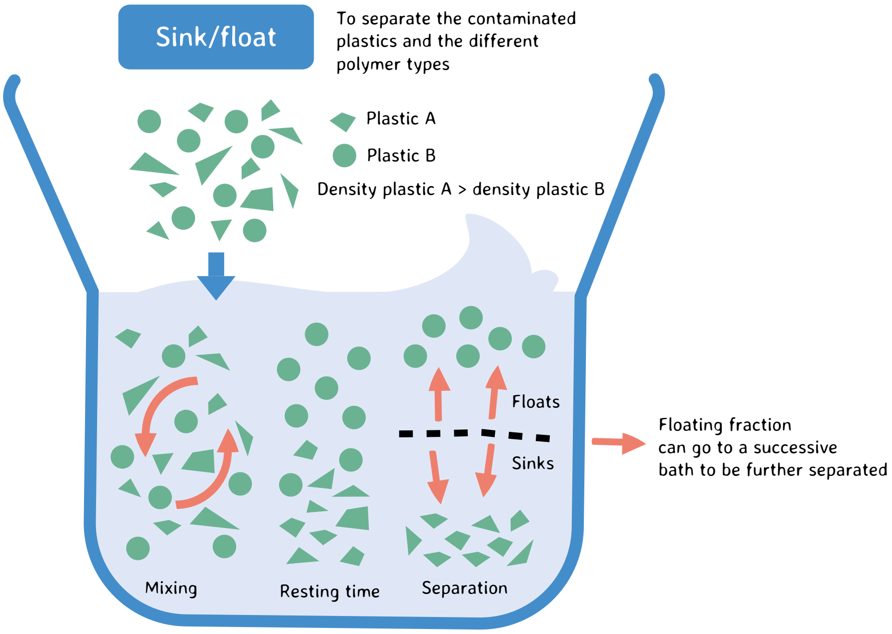


Figure 40. Schematic representation of the effect of the sink/float process on different types of plastic flakes.

Figure 41. Output WEEE fraction of the first sink/float bath, i.e., the one separated from the 'heavy fraction' (contaminated plastics).

Optical sorting

The use of elemental composition analysis, such as XRF, LIBS (laser-induced breakdown spectroscopy) or Raman MS, directly employed on the production line, is currently under development and among the less common separation techniques for critical Flame retardants (FRs) removal, namely brominated FRs. During the process, input material is spread evenly on the conveyor belt to avoid overlapping and allow the particles to lie flat, and the bromine concentration is detected using the sensor. Generally, a concentration of 2000 ppm bromine is used as the limit. The materials above and below the mentioned concentration are subsequently expelled using a jet of compressed air. This technique is still not able to distinguish between a plastic containing a restricted FR and a plastic containing a non-restricted FR.

NIR sorting

In general, NIR spectroscopy has the competency of separating WEEE/ELV plastics, such as PP, PS, ABS, and ABS/PC. Thus, it is commonly employed as it is suitable for polymer detection, rapid, and a non-destructive analysis method. On the other hand, black coloured plastics, which are widely used in both household appliances and vehicle parts, cannot be sorted by NIR light.

Electrostatic separation

Some recyclers use additional sorting technologies such as electrostatic sorting to further separate the styrenics into relatively pure polymer fractions (e.g. PS, ABS, filled PP). Since WEEE/ELV components are characterised by different conductivities, the electrostatic method is generally used for separating different types of plastics in the waste.

Colour sorting

A further sorting by colour is applied, for instance, for TEE plastics. The white colour fraction is separated from the non-white ones. For this purpose, the separators are equipped with high-speed cameras that monitor the moving layer of plastic under UV light.

Extrusion

The output of the recycling process, i.e., flakes of different polymers, is then extruded to produce plastic granulates.

PVC Stream

Separate collection of waste from the building and construction sector exists in most of the EU Member States. The collected waste is treated via mechanical recycling, which is currently the only process available to industrially recover post-consumer rigid PVC. The process (Figure 42) includes shredding, washing, grinding and sorting. Regranulation or compounding can complement the process as an additional step to produce PVC recyclates. The recycled PVC is then used again in the same industry sector: construction profiles and pipes.

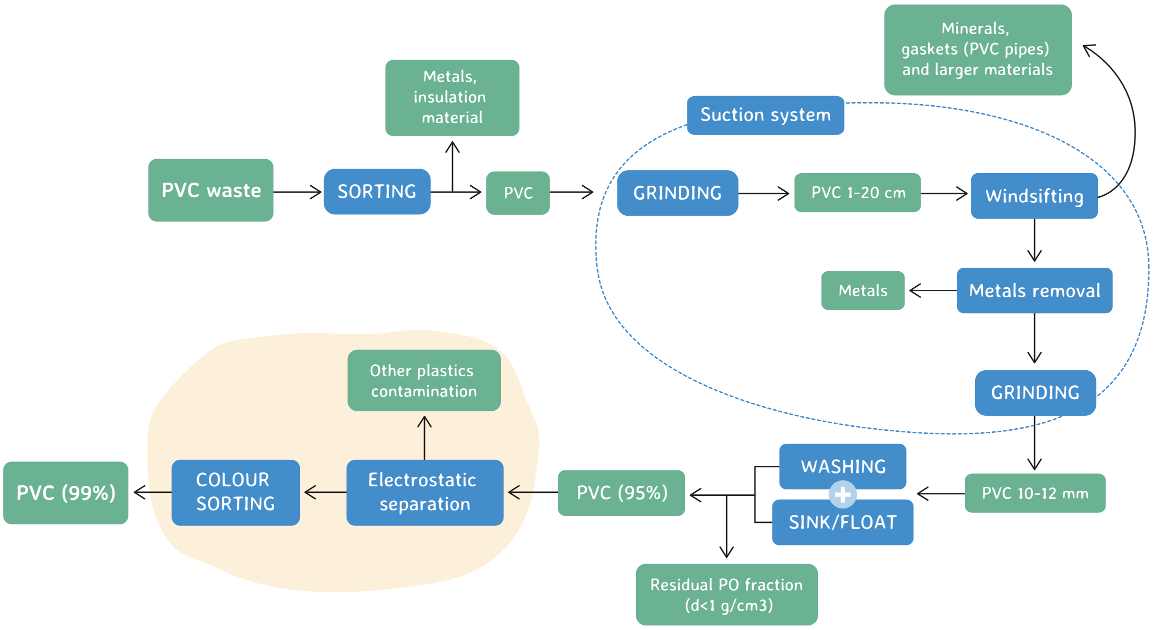


Figure 42. Exemplary flowchart of a PVC recycling line.

Rigid

Preparation Step

Specialised recyclers that treat rigid, and specifically *post-consumer,* PVC will either buy their input material from sorting centres or they will collect it directly from a construction site (Figure 43). Usually, as a first step, glass is taken out (e.g., window profiles), while metals and insulation materials can still be present in the input of the recycling process.

Figure 43. Mixed windows and door profiles, a typical incoming PVC rigid waste.

Size Reduction

Grinding

The first stage usually consists of one or several grinding steps, often coupled with dust suction systems. Shredders such as hammer mills and/or shredders with knives can be employed for this purpose. The resulting regrind (Figure 44) of this step is initially in the 1-20 cm size range, but is then further reduced to 10-12 mm in the following steps. Typically, grinding is paired with the removal of metal fractions (see: separation, *metal removal*).

Washing

Cold washing

Cold washing with the use of only water is carried out. In this step, the sink/float method is also applied (see later in the paragraph). Hence, the material is simultaneously cleaned and separated from other fractions (Figure 45).

Separation

Metal removal

During the first shredding of the input material, ferrous metals are taken out using magnetic separators, while non-ferrous metals are removed via eddy current.

Windsifting

Windsifting is employed to separate specific fractions/objects that might still be present in the stream, such as minerals, gaskets (PVC pipes) and larger materials, from the more fine, granulated PVC regrind.

Sink/float

Water tanks are used to perform the density separation (i.e., 'sink/float') step where small amounts of plastics with a density lower than 1 g/cm^3 are separated utilising flotation. This fraction is mainly composed of polyolefins (PP and PE), which are used in PVC profiles as protective veneers. At this point, the regrind is a fairly clean and homogeneous material, with a 'contamination' (e.g., other plastics, materials or metals) level of ca. 5 %.

Figure 44. Shredded PVC rigid waste.

Figure 45. Washed PVC regrind.

Electrostatic separation

Successive electrostatic separation steps allow for separating rubber and different types of plastics (ABS, Nylon, POs) according to their conductivity.

Colour sorting

The white colour fraction is separated from the non-white PVC fractions. For this purpose, employed separators are equipped with high-speed cameras that monitor the moving layer of plastic under UV light, to remove the coloured particles from white PVC regrind. This step, along with the previous electrostatic separation, allows reaching a ca. 99 % pure PVC regrind.

Extrusion

Extrusion with melt filtration is carried out at 140-170 °C and leads to further purification of the material (filter range is ca. 100-500 mesh). This way, the final granulates are made. In terms of the overall process, and according to our estimates, out of 100 kg of input material, ca. 70 Kg of high-quality recycled PVC can be produced. The rest is split between other materials and metals, the waste fraction that goes into incineration (ca. 10 %) and PVC contaminated with other plastics.

Flexible

According to the established practice, post-industrial flexible PVC (i.e., floor sheeting) mainly follows the recycling process of rigid PVC materials, except for the washing step, where the density sorting takes place. Thus, it is possible to refer to the scheme reported in Figure 42.

As for the other PVC flexible materials, there are specialised recyclers that are able to further process cable sheeting fractions to a relatively pure PVC recyclate.

Some use cryogenic micronisation since the different materials obtain a different particle size distribution. Afterwards, simple sieving can be used to selectively obtain flexible PVC with good purity. This is sufficient for sensitive applications such as wellingtons that are produced by injection moulding. There are a few others that might be able to achieve similar quality with other techniques or a combination of techniques (e.g., eddy current separation, grinding, and several steps of electrostatic separation).

However, a considerable fraction of raw cable sheeting material is not further sorted. Instead, it is used in a plastics conversion process called compression moulding where the tolerances for non-flexible PVC material or even non-melting material are very wide. This could give rise to artificial lumber or blocks of weight that are used to keep fences upright or to place road furniture.

Conclusion

The present section of the report thoroughly examined the current state of mechanical recycling processes across Europe, focusing on key plastic waste streams such as different packaging materials, Waste Electrical and Electronic Equipment (WEEE), End-of-Life Vehicles (ELV), and plastics for building and construction (particularly PVC). As seen throughout this section, each plastic waste stream has specific recycling requirements and challenges that often imply tailored collection, sorting, and recycling methods. For example, WEEE and ELV materials require complex depollution and dismantling steps before recycling, while plastic packaging must undergo extensive sorting due to contamination and the presence of multi-material components.

Notably, the efficiency of the presented recycling processes largely depends on the effectiveness of sorting technologies. Technologies such as near-infrared (NIR) scanning, density separation (sink/float), windsifting, and ballistic separation are essential for separating different plastic types. The section also emphasises the growing importance of artificial intelligence (AI) in optimising sorting and increasing the yield and purity of recyclates.

Common recycling units, here referred to as modules, were identified for the different streams such as size reduction (i.e., grinding), washing, separation, drying, and extrusion. These are consistently applied across different plastic types but are adapted in their parameters to meet the unique requirements of each stream.

Key challenges that are faced in the plastics recycling industry (mechanical recycling) are mainly contamination from labels, inks, and additives, as well as difficulties in recycling black, multi-layered and composite plastics. To address these issues, innovations in pre-sorting and label removal are to be complemented with design for recycling practices carried out upstream (i.e., by manufacturers and converters).

3

DISSOLUTION RECYCLING PROCESS

Context

Dissolution recycling (DR) is an innovative approach within the broader field of plastics recycling. It involves physical solvent-based processes in which targeted polymers can be selectively dissolved, separated from their additives, composites and other contaminants, and purified from sorted plastics waste fractions.

Depending on the processed feedstock, the following unit operations are performed. Dissolution purification is a polymer-targeted dissolution operation involving selectively extracting a targeted polymer from either a homogeneous or heterogeneous mixture. Dissolution treatment, a contaminants-targeted dissolution operation, focuses on selectively removing unwanted substances from a heterogeneous mixture (polymer composite) by dissolving or extracting these substances without fully or only partially dissolving the target polymer/plastic. Various combinations of process steps can be used to achieve either dissolution recycling processes.

Dissolution recycling falls under physical recycling technologies. Indeed, it is a physical process, as no chemical reaction takes place and chemical bonds within the polymer remain intact. This means that, just as in MR, and in contrast to CR, DR of waste polymers does not break them into monomers, so the overall polymeric structure of the plastic is not altered, and the polymers are recovered from the plastic waste stream.

Solvents can be chosen to dissolve a certain polymer at a given temperature, even if multiple polymers are physically attached, theoretically allowing a mixed feed to be separated into relatively pure product streams. Since the polymers are separated at the molecular level, most additives may also be extracted or left out of the extraction, resulting in a product with near virgin purity.[32,33]

Dissolution recycling involves a series of steps, hereafter referred to as "modules", that are used across various materials, each with its specific features. This is visualised in Figure 46.

Dissolution recycling offers several important advantages, making it a powerful option for achieving high-purity polymer recovery. One of its key strengths lies in its ability to selectively remove contaminants such as flame retardants, including brominated and aromatic types, during the purification process. This selectivity allows dissolution recycling to treat contaminated feedstocks. Additionally, dissolution processes are tolerant to moisture content, handling up to 5 % humidity in the feedstock, such as in applications like fish box recycling, without significant efficiency losses.

Dissolution recycling maintains the original polymer structure without shortening the polymer chains. The process achieves polymer-to-polymer recycling with full traceability, without the need for mass balance accounting. Because degraded polymer chains are selectively removed during the process, the final material shows enhanced mechanical and chemical properties, further aligning it with stringent application standards such as direct food contact use.

Yields in dissolution recycling are generally high, and greenhouse gas (GHG) emissions are low compared to the traditional fossil fuel-derived production of plastics. Losses primarily originate from the removal of polymer chains that degrade during the use phase, a necessary step to ensure the final product's quality. The purification operates at the molecular level, removing non-intentionally added substances (NIAS) and legacy contaminants. Solvent-based dissolution is capable of eliminating contaminants with high molecular weights up to 800–1000 g/mol.

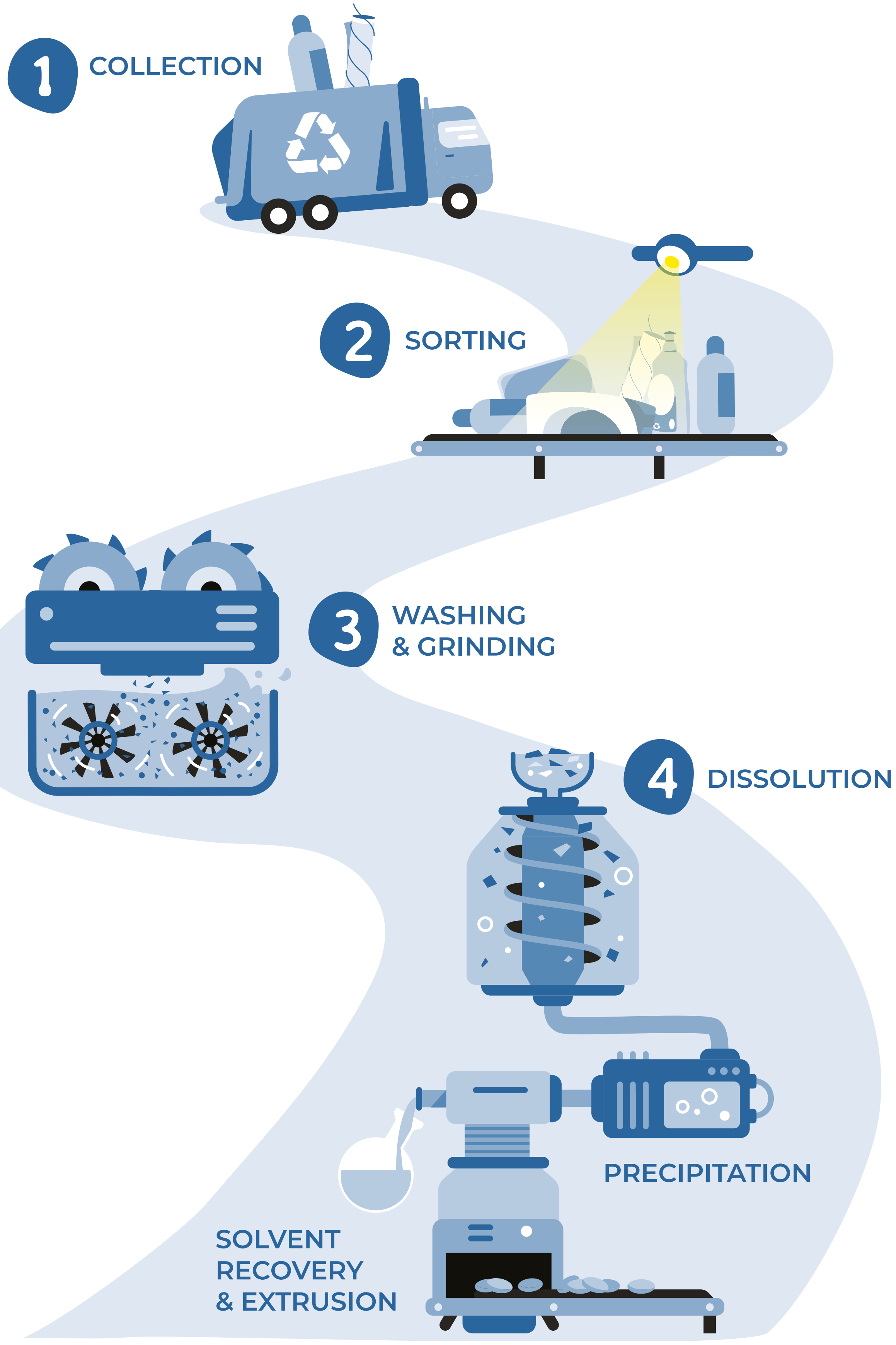


Figure 46: Dissolution Recycling flowchart.

This capability allows dissolution recycling to meet the purity requirements demanded for high-grade applications, such as food-contact HDPE.

Despite its many strengths, dissolution recyclers operating at scale face several technical challenges. Solvent selection is critical; the solvent must offer the right balance between selectivity for the target polymer, recyclability, cost, toxicity, and flammability. Process conditions such as temperature, pressure, and solvent-to-polymer ratios, as well as the use of antisolvents where applicable, must be precisely tuned to ensure successful purification.

Another major challenge lies in contaminants control. A detailed understanding of the contaminant profile in the input waste is essential for effective purification. However, there is often a lack of clarity around the specific impurities addressed by different technologies, with many recyclers simply referring to “contaminants” in general[34]. While, in theory, dissolution recycling could purify mixed-polymer waste streams through sequential solvent treatments, in practice, the increased complexity and resource demands have led most technologies to focus on single-polymer streams. In these single-polymer streams, dissolution recycling is highly effective at removing NIAS, including processing aids, stabilisers, and other similar impurities.

The choice of solvent is particularly important for food-grade applications. The use of hazardous or toxic solvents can limit the end-use of the recycled polymer, necessitating additional and often energy-intensive drying steps to ensure the removal of residual solvent.

Economically, the success of dissolution recycling may also hinge on recovering and valorising by-products, which is performed by some recyclers. Some technologies aim not only to recycle the solvent but also to extract and reuse the removed contaminants. While data transparency remains limited, this approach is increasingly seen as necessary for achieving operational viability, even at pilot scale.

Due to the complexity of solvent chemistry and process engineering, dissolution recycling requires significant expertise and investment. While multinational companies and large industrial players often develop these (large-scale) processes due to their extensive petrochemical knowledge, independent companies have also emerged as leaders in this field. As a modular approach can be taken when building dissolution recycling plants, capacities can be increased by installing more modules. In Figure 47, the exterior view of the dissolution plant is shown, highlighting its infrastructure and layout.

Figure 47: Dissolution plant.

Dissolution Recycling Modules

Preparation Steps

As plastic waste is collected, with other plastic, or mixed with metal, paper, and other waste, it enters the system from various sources, including source-separated collection such as household and commercial recycling streams, as well as mixed waste streams like municipal solid waste containing metals, paper, or food residues. While source-separated collection improves the purity of the feedstock, mixed waste streams require more advanced sorting and cleaning processes downstream.

Accurate sorting is critical for maximizing process efficiency. While processes might still function with a feedstock containing, for example, only 50 % of the target polymer, this would significantly reduce the available purification capacity. Current sorting technologies are very similar to the ones described in the Sorting chapter, including near-infrared (NIR) and Visual Inertial Systems (VIS) for polymer recognition, as well as Artificial Intelligence (AI) for material and object-level identification. These systems sort plastics by polymer type (e.g., PE, PP, PET, PS) and even by product format. Colour-sorting is less relevant for DR since most contamination linked to colours (pigments, inks) can be removed. Sorting, curation, and blending of different feedstocks are required to adjust the molecular weight distribution of the resulting product.

Once sorted, a densification step usually takes place where plastics are shredded or ground into flakes, regrinds, agglomerated films, pellets, or densified waste streams. The washing process then removes surface contaminants such as adhesives, dirt, and food residue, as well as labels and inks, which can be problematic during dissolution. Additionally, (hot) washing can eliminate volatile and low molecular weight (MW) contaminants.

Depending on the plant layout and strategy (some dissolution recyclers are also mechanical recyclers, for example), washing and grinding may occur on-site, directly at an MR line, or off-site, with flakes shipped to centralised dissolution units. For recyclers having multiple recycling lines like MR and DR, the flakes can then serve as a versatile intermediate, which can be processed further or purified based on market demand and application.

Dissolution

What: Dissolution recycling technologies are recycling technologies that recover polymers from plastic waste in a solvent-based physical recycling process, which intends to keep polymer chains intact and performs, depending on the processed feedstock, the following unit operations:

1. Dissolution purification of a target polymer (also referred to as "extraction"), selectively removing a polymer from a homogeneous or heterogeneous mixture or;

2. Dissolution treatment of a target polymer (also referred to as "washing"), selectively removing unwanted materials from a heterogeneous mixture (polymer composite) by dissolving or extracting unwanted materials without or only partly dissolving the target polymer/plastic.

And different combinations of process steps to perform 1. or 2.

How: At its core, polymer-targeted dissolution purification, which is the more widely implemented DR process, exploits the selective solubility of polymers in specific solvents. When prepared, plastic waste is introduced into a solvent:

- The target polymer (e.g., PE, PP, PS) dissolves into the solvent, forming a homogeneous polymer solution.

- Most contaminants (e.g., pigments, fillers, other polymers, stabilisers, flame retardants, or degradation byproducts) remain undissolved or insoluble. This allows for a physical separation of the desired polymer from various unwanted substances.

In some cases, the dissolution process involves two stages: in the first stage, soluble contaminants are removed while the polymer remains insoluble. In the second stage, the temperature and/or pressure are adjusted so that the polymer becomes soluble in the solvent, while the remaining contaminants stay insoluble.

An important distinction to be aware of is that dissolution is not melting. The polymer remains chemically unchanged and does not reach its melting point during the dissolution stage. It transitions from solid to solution phase directly or, in some cases, it is molten before dissolving in the solvent.

Process steps

Mixing and dissolution

The plastic flakes, regrinds, pellets, or agglomerates are introduced into a solvent tailored to the specific polymer in a dissolution tank, as shown in Figure 48. Common solvent options include non-polar solvents like alkanes (e.g., heptane, hexane, methylcyclohexane) for PP and PE, or aromatic solvents like toluene, cymene or limonene for PS.

The system is maintained under controlled temperature and pressure to ensure selective dissolution.

Dissolution temperatures generally range from 50 °C to 250 °C, depending on polymer type and solvent choice. The duration may vary from 30 minutes to several hours. For some technologies, pressure is applied (e.g., 0.5–5 MPa), especially when low-boiling solvents are used.

Figure 48: Dissolution tank.

Contaminant separation 1

The polymer solution has a sufficiently low viscosity to enable the application of conventional separation methods like filtration (for example, using a classifier, as shown in Figure 49), sedimentation, decantation and adsorption. After dissolution, the remaining solid residue, which includes labels, additives, fillers, and incompatible polymers, is filtered or centrifuged out. Some processes use multiple solvents or sequential dissolution stages to address contaminants that partially dissolve in the primary solvent.

Contaminant separation 2

Once the large impurities have been removed through filtration or centrifugation, the dissolved polymer solution may still contain smaller insoluble impurities such as dyes, graphite, lime, or low-molecular-weight degradation products. To address this, the solution undergoes further purification steps designed to target and remove these remaining contaminants. Techniques can include adsorption (e.g., activated carbon), liquid–liquid extraction, or selective precipitation of impurities. The choice of purification method depends on the chemical nature of the contaminants, their concentration, and the purity requirements of the final application. For applications such as food-contact materials or medical-grade plastics, stringent thresholds may necessitate multiple purification stages to ensure compliance with regulatory standards (e.g., EFSA, FDA).

Precipitation (recovery)

The clean polymer is recovered from the solution, separating it from the solvent and remaining soluble impurities using one of the following, or a combination of the following methods:

- **Solvent–Antisolvent Method (SA):** A non-solvent (e.g., methanol, water, hexane) is added to cause the polymer to precipitate.
- **Temperature-Swing (TS):** The solution is cooled, reducing polymer solubility and triggering precipitation.
- **Supercritical Solvent (SS):** Supercritical fluids (e.g., propane) are used to dissolve and precipitate the polymer via precise pressure and temperature control.[35] This can allow for a deep decontamination of the polymer thanks to the different flow characteristics of the solvent in supercritical state.

The polymer precipitates as a paste, which is then washed and/or dried. The solvent containing the dissolved polymer can be recovered from the solution, for example, by letting it enter a vacuum vessel for solvent extraction. This allows for the reuse of the solvent in subsequent recycling cycles, reducing waste and cost.

Figure 49: Close-up of a classifier used in dissolution recycling for separating particles after the dissolution process.

Post-processing

The precipitated polymer is then filtered and washed to remove any residual solvent or antisolvent. While drying (typically at 80–120 °C) is often employed to further remove residual solvents, it can be considered optional. In some cases, the polymer can be directly fed into a degassing extruder to achieve solvent removal. To improve selectivity, multiple dissolution and precipitation stages may be employed using different solvents or techniques.

Devolatilisation vessels can be used to separate the polymer from the solvents in a continuous way. Several stages may be used to reach low residual volatile content in the final polymer. Devolatilisation relies on tailored designed pre-heater and devolatilisation vessels as well as low shear melt pumps. The solvent is recovered and purified for further use to meet economic and environmental requirements.

Alternative dissolution approaches

In the steps that are described above, a polymer-targeted dissolution process (called dissolution purification) is described. This is the most common approach, where a solvent is chosen for its affinity to the target polymer to be recycled while rejecting other materials. However, an alternative dissolution approach, called dissolution treatment, can be taken as well.

In that case, some solvents or solvent stages are used specifically to extract additives or low-MW contaminants, without fully dissolving the polymer.

Another technique is solvent washing, that can be considered as an intermediate approach between mechanical and dissolution recycling. Instead of dissolving the polymer matrix, solvents are used to remove surface-level contaminants and additives that migrated into the material after its formation. These include printing inks, glues, odours, and NIAS. Solvent washing is especially relevant for flexible films, where visual and olfactory quality is key. However, as it is not effective for removing masterbatch colourants or bulk additives, pre-sorting of clear or white fractions is still necessary.

These processes are typically performed at mild conditions, around 50–70 °C and ambient pressure, with standard industrial solvents. They are integrated into sorting and washing lines that include cold water rinses, flotation steps, mechanical drying, and eventually extrusion of the cleaned polymer. Compared to full polymer dissolution, these methods are less energy-intensive and potentially more cost-effective for certain waste fractions.

Delamination technologies use solvents to dissolve interlayer adhesives in multilayer plastics or composite structures such as packaging laminates, automotive panels, and battery casings. By targeting the adhesive layers, delamination enables the separation and recovery of individual materials. This approach is currently one of the most commercially viable routes for handling multilayer waste, helping unlock streams that are otherwise considered non-recyclable[36]. The delamination technique can also be considered as an intermediate approach between mechanical and dissolution recycling. However, design for recycling should avoid producing multilayer packaging to facilitate sorting and enhance the recyclability of the packaging.

In some cases, dissolution processes can retain certain additives within the polymer, which can be beneficial for the intended application of the recycled material. This selective retention allows for the preservation of desirable properties such as colour, UV resistance, or flame retardancy, reducing the need for additional additives (like carbon black for example) during the manufacturing of new products. By maintaining these functional additives, the dissolution process not only enhances the efficiency of recycling but also supports the production of high-quality, application-specific recycled plastics.

Extrusion

The extrusion step in dissolution recycling is the phase where the purified polymer is transformed into a usable form. After the polymer has been dissolved, separated from contaminants, and purified, it undergoes extrusion to form pellets. This process involves several key stages that are also used in virgin polymer production plants:

- **Melting:** The purified polymer is fed into an extruder, where it is heated and melted. The extruder typically consists of a heated barrel and a rotating screw that pushes the polymer through the barrel.
- **Decontamination:** During extrusion, any remaining volatile contaminants are removed, including low-molecular-weight components and solvents. This is achieved through a filtration step and the application of vacuum vents or degassing zones within the extruder, ensuring the final product is free from impurities. This step can also refer to polymer degassing or devolatilisation.
- **Shaping:** The molten polymer is then forced through a die to shape it. The shaped polymer is subsequently cooled and solidified. Typically, water ring or underwater pelletising systems are used.
- **Pelletising:** The shaped polymer is cut into uniform pellets, which are the final product of the extrusion process. These pellets can then be used as raw material for manufacturing new plastic products.

These steps convert the purified polymer into a standardised form that is easy to handle, transport, and use in various applications. The quality of the extruded pellets directly impacts the performance and properties of the recycled plastic. Extrusion includes a compounding step, where stabilisers and performance additives (that are typically removed during the DR process) are (re)introduced. Figure 50 illustrates pellets produced by a dissolution recycling process.

However, not all dissolution recycling processes include extrusion as a final step. Alternatively, following a devolatilisation step, the molten polymer directly goes through the following "shaping" and "pelletising" steps and does not need to go through an extruder. Before these steps, re-additivation of the clean polymer with stabilisers is done. In some cases, the recycled polymer can also be recovered as a dry powder or flake after multiple (degassing) purification stages, precipitation and drying, especially when the material is intended for compounding or further processing by the end-user. This allows for greater flexibility in downstream applications and avoids duplicating extrusion steps that converters may already perform.

Figure 50: Close-up of pellet crystals produced by a dissolution recycling process.

Solvent Purification

In dissolution recycling, maintaining the purity of solvents is essential to ensure the quality and consistency of the recycled polymers. Over time, solvents that are recovered and reused can accumulate impurities, which can compromise the dissolution and precipitation steps, ultimately affecting polymer purity and process efficiency. Effective solvent recovery and purification are therefore critical not only for maintaining product quality but also for minimising environmental impact and reducing operational costs.

Distillation remains the most widely used technique for solvent purification in dissolution recycling plants. It offers a reliable method to separate components from fluid mixtures across a broad range of concentrations and flow rates, delivering high-purity recovered solvents. However, because solvent recovery may require multiple distillation stages to fully remove impurities, optimising the design and operation of the recovery system is key. Advanced distillation technologies and properly engineered column internals, such as structured packing, random packing, trays, and phase separators, can enhance separation efficiency, increase throughput, and reduce energy consumption.

In DR plants, well-designed purification systems significantly extend the life of solvents, reducing the need for fresh solvent production and thereby lowering the overall environmental footprint of the process. Efficient solvent recovery also supports broader sustainability objectives by minimising waste and conserving resources, further enhancing the economic and environmental viability of dissolution recycling technologies.

Quality Control

In dissolution recycling, quality control is essential to ensure that the recovered polymers are compliant with product legislation and meet performance standards for reuse, including in high-demand applications such as food contact. The process is inherently selective, enabling the removal of non-target additives, degraded polymer chains, and substances of concern, but rigorous monitoring remains vital to validate this effectiveness.Key quality control measures include:

1. **Feedstock characterisation**
   Prior to processing, incoming plastic waste is analysed to identify polymer types, additive profiles, and contamination levels. This enables the selection of appropriate solvents and process parameters, and ensures compatibility with regulatory thresholds (e.g., for food-grade recycling).
2. **Solvent and process monitoring**
   The purity of solvents and control over dissolution conditions (temperature, pressure, solvent-to-feed ratios) are regularly verified. Accumulated impurities in solvents can compromise polymer quality, so closed-loop purification systems (e.g., distillation) are often integrated and monitored for efficiency.
3. **Polymer purity assessment**
   Post-dissolution, the regenerated polymer can be tested using techniques such as FTIR, DSC, and chromatography to confirm the removal of additives (e.g., plasticisers, flame retardants) and non-intentionally added substances (NIAS). The aim is to reach impurity levels acceptable under EU regulations and EFSA guidelines and/or voluntary initiatives like CosPaTox.
4. **Residual solvent analysis**
   Ensuring minimal residual solvent in the final product is critical, especially for sensitive applications. Target thresholds (often <0.1 % w/w) are achieved through optimised washing and drying steps and verified through analytical testing (e.g., GC-MS).
5. **Pellet quality and consistency**
   Once re-extruded, pellets undergo mechanical and rheological testing (e.g., microscopy, tensile strength) to ensure performance comparable to virgin polymers. Batch-to-batch consistency is tracked to support downstream manufacturing reliability.

These quality control protocols help ensure that dissolution recycling produces polymers that are not only high in purity and functionality but also compliant with circular economy goals and regulatory standards.

Dissolution Recycling Technologies

In this section, the modules mentioned in the previous chapter, such as *Preparation steps, Dissolution* and *Extrusion* will be further elaborated according to the different types of plastic waste streams treated for recycling. For each stream, the basic modules have been kept and complemented by adding some sub-units when necessary to ensure the most complete level of detail. Specific recycling technologies are highlighted in the following colours: dark green corresponds to a technology widely employed in the plastic recycling industry, light green represents a technology with a medium level of implementation, yellow corresponds to a technology with low level of implementation, orange refers to technologies which are currently under development and used by very few recyclers at the industrial scale, while red represents technologies currently under lab-scale development and not used by recyclers at the industrial scale.

In this section, PP, PE and PS dissolution will be further explained, as these are currently the main technologies where most production capacity is (to be) installed in the dissolution recycling industry. Other waste streams that can be recycled through dissolution include ABS.

PE and PP stream

LDPE and HDPE are sometimes recycled together, depending on the specific recycling process and the desired end product. In other cases, they are recycled separately to maintain the distinct properties of each polymer. Dissolution recycling of polyethylene (PE), including both low-density (LDPE) and high-density (HDPE) types, is an emerging strategy for recovering high-quality polymer from mixed or contaminated plastic waste. Similarly, dissolution recycling is an advanced method for purifying reclaimed polypropylene (PP), from post-consumer or post-industrial waste streams. These processes utilise specific solvents under controlled conditions to dissolve PE or PP, enabling the separation of contaminants and the recovery of high-purity material. It is important to note that PE and PP, despite having similar dissolution recycling processes, are not recycled together due to their differing properties. Therefore, careful separation of PE and PP is essential before the dissolution process, as some solvents are selective to polyolefins in general and could potentially dissolve both materials.

A flowchart for dissolution recycling of PE or PP waste is shown in Figure 51.

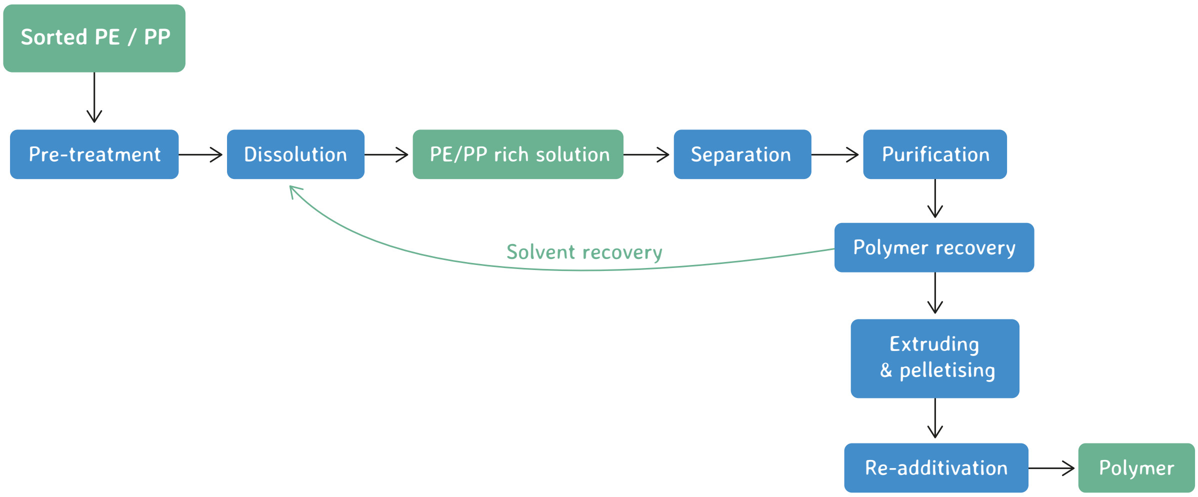


Figure 51: Process flow - dissolution of PE or PP waste.

General process overview

1. Waste preparation

PE- or PP-containing waste is first cleaned (if necessary), shredded, and optionally pre-sorted. These steps increase surface area and improve solvent accessibility during dissolution. Typical recycling plants include separation and washing stages before the dissolution reactor to remove foreign materials like paper labels from polyolefin material. Separation stages may include metal separators, label removers, ballistic sorters, bottle sorters, manual sorting, air classifiers, float-sink separation, and NIR spectroscopy. Washing stages may involve water with washing-active substances, hot water, and rinsing. The polymer material is dried before entering the dissolution reactor, with a dryer placed between the separation/ washing stages and the (swelling) reactor. As the dissolution process can remove non polyolefin polymers, additives, fillers, oxidants and most other contaminants, it is crucial to remove non-targeted polyolefins. Therefore, when recycling PE, PP should be carefully separated before entering the reactor, and vice versa.

2. Selective dissolution

Plastic flakes are introduced into a fluid non-polar solvent that selectively dissolves PE or PP under elevated temperature and pressure. Depending on the solvent and polymer grade, dissolution typically occurs between 100 °C and 250 °C, often near but below the polymer's melting point. Supercritical conditions can be reached for the solvent. Solvent options may include alkanes (e.g., n-butane, propane, n-hexane, n-heptane) or proprietary solvent blends. Some systems may include a swelling step, where the polymer is partially swollen in a solvent to release trapped contaminants before full dissolution. A swollen polymer has larger molecular distances and lower density, making it more voluminous. This allows impurities to diffuse out more quickly compared to an unswollen polymer. Additionally, squeezing the swollen polymer mechanically can remove impurities, and removing the swelling solvent can also carry away contaminants.

3. Contaminant separation

During or after dissolution, insoluble materials, such as pigments, fillers, adhesives, or other plastics, are separated from the polymer solution through filtration or sedimentation, relying on gravitational or centrifugal forces.

4. Purification

The clarified PE or PP solution can be contacted with solid media at the dissolution temperature and pressure. This step aids in further purification by adsorbing residual contaminants, resulting in a polymer product with properties that are similar to virgin PE or PP.

5. Polymer recovery

The purified polymer is recovered by precipitating it from the solvent. This can be achieved by cooling the solution or adding an antisolvent that reduces polymer solubility. The target polymer solidifies while the solvent remains in the liquid phase. Due to the solvent's volatility, this can also be achieved through depressurisation or temperature reduction, causing the polymer to crystallise and precipitate. The solvent can then be recycled for subsequent use.

6. Extruding and pelletising

The recovered polymer can be dried to remove residual solvent. What remains is a purified, solid PE or PP material, often in flake, powder, or paste form. To make this material usable in manufacturing, it is melted and extruded into a uniform flow of molten plastic, then cut into pellets (using strand or underwater pelletising systems). These pellets are the standard industrial feedstock used for injection moulding, extrusion, or film production. This can include a re-additivation step where additives such as stabilisers, antioxidants, or processing aids may be reintroduced to restore properties lost during purification. Solvents are typically recycled in a closed-loop system for sustainability.

PARAMETER	TYPICAL RANGE
Solvent Type	Non-polar (e.g., n-butane, propane, n-hexane, heptane, or mixtures thereof)
Dissolution Temp.	100 °C – 250 °C
Pressure	0.5-30 MPa
PE / PP Concentration	Up to ~20 % w/w in solvent
Precipitation Method	Cooling or non-solvent addition, contact with solid media at dissolution conditions
Drying Temp.	80 °C – 120 °C

Table 3: Key Process Parameters (General Range).

PS stream

Dissolution recycling is an advanced method for recovering polystyrene (PS) and polystyrene copolymers from post-consumer and industrial waste streams, aiming to produce high-purity recycled material suitable for reuse in various applications. Recent developments describe multiple solvent-based processes optimised for PS purification, including the treatment of materials containing hazardous additives like brominated flame retardants. A flowchart for dissolution recycling of polystyrene waste is shown in Figure 52.

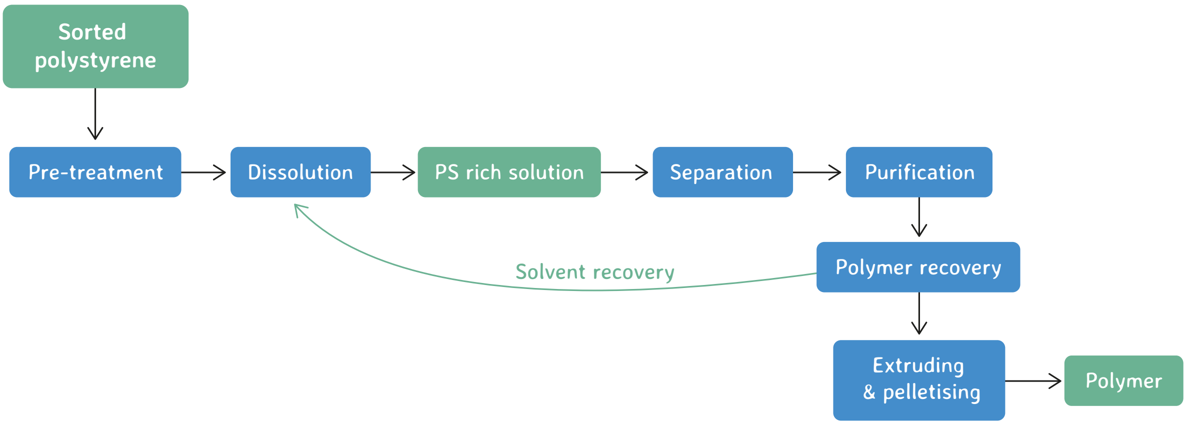


Figure 52: Process flow - dissolution of PS waste.

Process description

1. Pre-treatment

PS waste is first sorted to remove non-target polymers and contaminants like metals, adhesives, or food residues. This sorting is crucial for various sectors, such as PS with brominated flame retardants (BFR) from Waste Electrical and Electronic Equipment (WEEE) and End-of-Life Vehicles (ELV), as well as expanded PS (EPS) from construction and demolition. Size reduction, particularly for EPS, increases surface area and improves dissolution rates. Drying the material is also important, as moisture can interfere with solvent performance and process stability.

Additional cleaning steps, such as light washing, may reduce the burden on filtration systems, while densification helps in handling low-density foams. These pre-treatment measures improve solvent efficiency, reduce downstream purification needs, and help ensure a high-quality recycled polymer.

2. Solubilisation

PS waste, including general purpose polystyrene like expanded polystyrene (EPS), is dissolved in selective organic solvents such as p-cymene or ethylbenzene under controlled conditions. Both solvents exhibit excellent solubility for PS, while non-target materials, including copolymers, adhesives, and fillers, remain undissolved. However, the dissolution of High Impact Polystyrene, which is prevalent in post-consumer packaging, can be more challenging due to its composition. Closed and vented dissolution systems, sometimes featuring submerged grids, are used to maximise contact efficiency and reduce dissolution times. PS solubility in these solvents typically reaches around 30–35 % by weight at room temperature, though higher concentrations can slow down the dissolution kinetics.

3. Filtration

Following dissolution, the polymer solution is filtered through a multi-stage system, beginning with coarse filtration and moving to finer stages, to remove undissolved solids such as metals, pigments, multilayer barriers, and degraded copolymer fractions.

4. Precipitation and washing

Precipitation of the purified PS is induced by introducing the solvent-polymer solution into a non-solvent such as boiling hexane or heptane. A typical first wash uses a 1:3 volume ratio (PS solution to hydrocarbon) with moderate mechanical agitation to accelerate solvent diffusion and polymer precipitation. Further washing steps with fresh heptane at around 1:1 volume ratios refine the purity by removing residual solvents and low molecular weight impurities. In some cases, an optional third wash is employed to reduce residual solvent content below 0.1 %, critical for controlling the melt flow index (MFI) and mechanical properties of the final material.

5. Drying

After washing, the PS is dried at approximately 120 °C to remove remaining solvents, ensuring a stable material for further processing.

6. Extruding & pelletising

The purified, dried PS is then extruded at temperatures between 140 °C and 160 °C to form pellets ready for reuse in manufacturing.

PARAMETER	TYPICAL RANGE/CONDITION
Solvent Options	p-cymene, ethylbenzene, or mixtures
PS Solubility Limit	~30–35 % w/w at room temperature
First Wash Solvent	Hexane (~69 °C boiling point) or heptane (~98 °C)
Volume Ratio (First Wash)	1:3 (PS solution to hydrocarbon)
Volume Ratio (Second Wash)	1:1
Drying Temperature	~120 °C
Extrusion Temperature	140 °C–160 °C

Table 4: Key Process Parameters (General Range).

Conclusion

This chapter has provided a comprehensive overview of dissolution recycling processes and technologies, emphasising their relevance, particularly for hard-to-recycle plastic waste streams. Dissolution recycling enables the targeted purification of specific polymers, such as PE, PP, and PS, by leveraging selective solvent interactions to separate polymers from additives, contaminants, and composite materials.

A modular approach to dissolution recycling has been outlined, encompassing key stages such as feedstock preparation, dissolution, filtration, precipitation, washing, drying, extrusion, and solvent recovery. These steps are carefully optimised depending on the polymer and solvent system used, with solvent purification and quality control playing essential roles in ensuring the circular use of solvents and the production of high-quality recycled polymers.

The chapter also highlights that while dissolution recycling is still an emerging industrial practice, it holds potential for improving the purity and performance of recycled plastics thanks to key advantages like contamination removal and achieving polymer-to-polymer recycling. This is especially critical in the context of increasing availability of recyclates suitable for sensitive applications, including food contact and technical uses.

Although the technology shows promise, particularly for hard-to-recycle streams, its deployment remains limited to a small number of pilot and early commercial plants, often backed by significant industrial investment. It is expected that multiple new DR plants will be installed in the next 3 to 7 years (driven by legislative market needs for high-quality post-consumer recyclates, amongst others). Most existing applications focus on mono-streams with relatively known compositions, as broader feedstock flexibility would require more advanced solvent systems and additional process complexity. Furthermore, the use of organic solvents introduces challenges related to safety, environmental impact, and regulatory compliance, especially when targeting food-grade outputs.

4

CHEMICAL RECYCLING PROCESS

Context

Chemical recycling involves various processes that use chemicals to break down plastic waste into its original monomers or other valuable chemicals using chemical reactions[37,38]. These processes might have the potential to contribute to the circular economy by converting plastic waste into valuable raw materials. An advantage of chemical recycling is the high quality of the final products, which in some cases does not differ from the quality of the original fossil fuel-derived ones. However, its implementation has been slow due to technical and economic challenges, as well as a lack of clear regulatory frameworks. The absence of a well-defined legislative framework has hindered development and discouraged companies from investing in this sector. Despite these challenges, the industry is expected to grow, although the legislative framework has yet to facilitate this anticipated expansion.

It is due to this section that we introduced the dark red highlight for technologies, referring to lab scale development or 0% technology implementation. As they are not usually applied, these technologies will be highlighted in dark red in the chemical recycling modules section, whereas other colour codes are given in the section of chemical recycling technologies. It is important to note that pyrolysis, a process that breaks down plastics into smaller molecules, is more widely used than depolymerisation, but it is not suitable for all kinds of plastics. For example, it cannot be used for PET. However, there is a notable lack of publicly available or shareable data on these technologies.

Chemical recycling (CR) involves a series of steps, hereafter referred to as “modules”, that are used across various materials, each with its own specific features. Below is a summary of these modules, split into two pathways: thermal decomposition, commonly applied for chemical recycling of polyolefins, and chemical depolymerisation, commonly applied for chemical recycling of polyesters.

It is important to keep in mind that the modules detailed below are ideally preceded by other sorting or mechanical recycling modules, as reported in the Sorting processes chapter.

While a generic description is provided here, specific details about the different waste streams are reported in the Chemical recycling technologies chapter. It must be noted that not all units will be applicable to each stream presented in the next section.

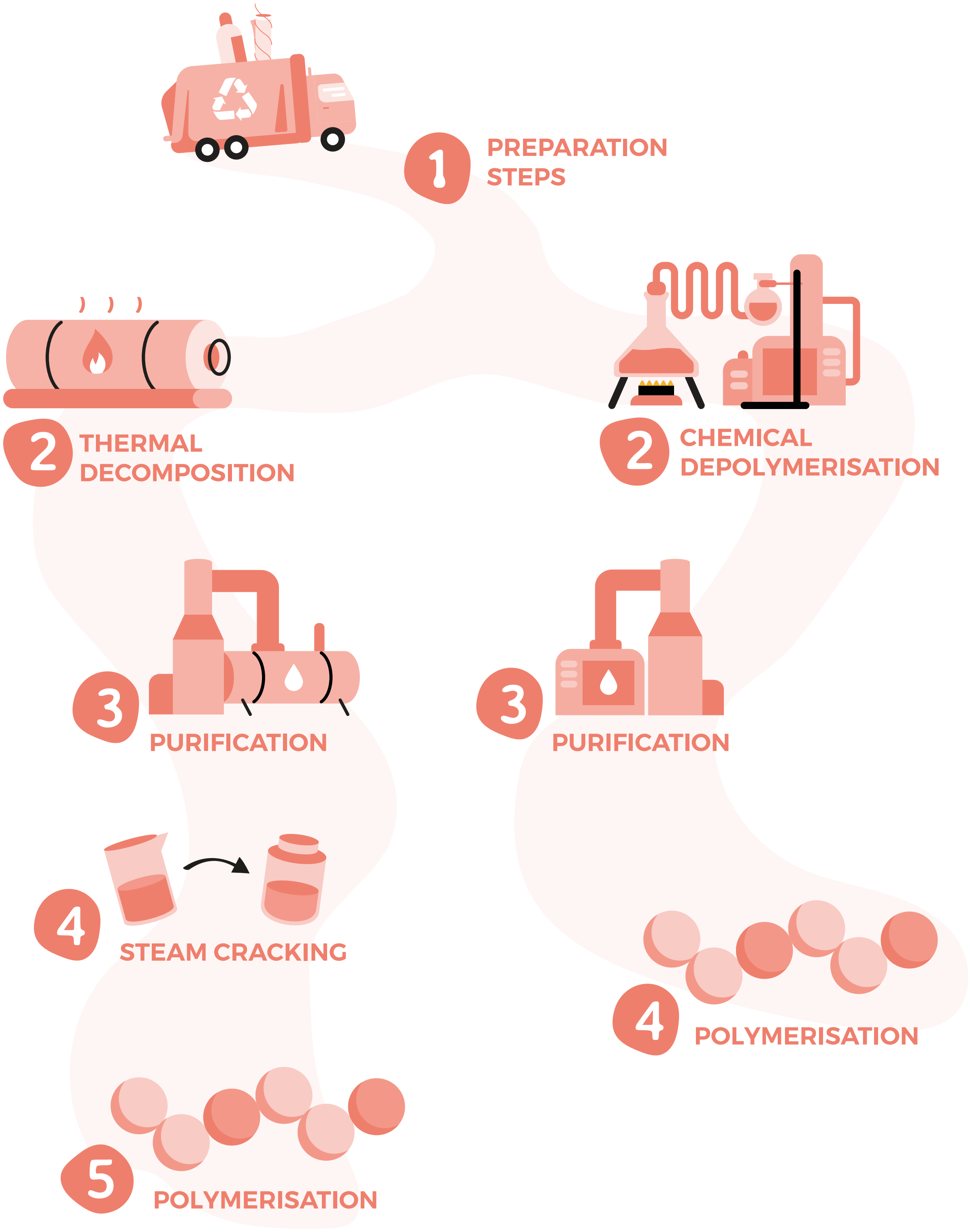


Figure 53: Chemical Recycling flowchart.

Chemical Recycling Modules

Preparation Steps

Feedstock preparation is a critical stage in chemical recycling, ensuring the efficiency and stability of the process while balancing economic feasibility.

Typical contaminants that should not be present above certain limits, like PVC and other halogenated materials, pose significant issues, as their decomposition releases acidic gases like hydrogen chloride, which can corrode equipment and require complex gas-cleaning systems. For this reason, careful sorting and pre-treatment are still necessary to ensure stable operation. In terms of purity requirements, chemical recyclers can process waste bales containing 85-95 wt. % of the targeted polymer. The main limiting contamination components include moisture, paper and organics, metals and non-targeted polymers.

Mixed polyolefins (PO), including polyethylene (PE) and polypropylene (PP), with contamination levels, inconsistent polymer blends, and multilayer films with oxygen barriers, often end up in waste-to-energy processes or landfills. Ideally, a mono-material approach is recommended to facilitate the sorting and the recyclability of the packaging. If needed, however, chemical recycling processes, particularly thermal degradation processes, can be useful for handling these multilayer films, post-consumer packaging, and industrial film waste.

From a logistical point of view, the channelling of (hard-to-recycle) feedstock towards CR needs to be optimised, as many of these waste fractions still end up being incinerated when they are not accepted by mechanical recyclers.

In addition to purity, the physical characteristics of plastic waste, such as size and density, play a crucial role in the preparation steps for chemical recycling processes. Properly sizing the plastic feedstock ensures efficient handling and processing within the recycling equipment. For instance, shredding or granulating the plastics into smaller, uniform pieces can enhance the efficiency of subsequent thermal or chemical treatments. Similarly, the density of the plastic material can affect the separation and sorting processes, ensuring that different types of plastics are appropriately categorised and processed. Addressing these physical attributes is essential for optimising the overall efficiency and effectiveness of chemical recycling operations.

Specialised chemical recyclers might apply some preparatory steps before the process to ensure a smooth and efficient run of the line. For instance, many recyclers carry out further sorting before running the material through their line. These steps differ depending on the treated stream. Other preparation steps might be linked to preceding mechanical recycling modules, creating waste residuals that can be considered for CR. In general, the preparation steps are very similar to the ones applied in MR, described in the Sorting section of this report.

Thermal Decomposition

What: Thermal decomposition is a process that breaks down polymers into smaller molecules through the application of heat. This method is used to convert plastic waste into valuable products such as chemicals and fuels. In general, these chemicals can then be used in monomer-producing steam crackers (as a naphtha substitute), similarly to the monomer production from fossil fuel-derived feedstock. The main idea of the recycling process is to cut the polymers to chains short enough compared to gasoil or naphtha, with carbon numbers between 20 and 40 being targeted.

How: The process involves heating the plastic waste to high temperatures and a controlled amount of oxygen, causing the polymer chains to break down without burning them. This generates hydrocarbon fragments that can go through purification steps and steam cracking for the recovery of the products.

Most thermal decomposition technologies focus on polymers such as polyolefins and polystyrene. This focus is because these polymers primarily produce hydrocarbons, which are the desired output molecules. In contrast, polymers with functional groups, like PET and PVC, yield more complex mixtures that are harder to process into simple hydrocarbons. The thermal degradation process typically involves random bond scission along the polymer chain, unlike the controlled breakdown in chemical depolymerisation (as will be explained in the section on Chemical depolymerisation). Consequently, the resulting pyrolysis oil or syngas contains a mix of hydrocarbon products. The diverse mixture of products includes hydrocarbon liquids and gases, as well as char along with impurities or contaminants of other chemical nature.[39]

Thermal decomposition can be approached in two main ways, depending on the use of oxygen. Pyrolysis, also called thermal cracking, involves high temperatures in the absence of oxygen, while gasification uses a small amount of oxygen to help break down materials at even higher temperatures. Controlling the amount of oxygen and the reaction conditions is essential to ensure proper degradation and to prevent the plastic from incinerating.

Pyrolysis

Pyrolysis generally occurs in the absence of oxygen at temperatures ranging from 300 to 700 °C and under atmospheric pressure, producing a liquid called pyrolysis oil, along with char and gaseous by-products. During pyrolysis, the waste is introduced into the reactor as extruded molten material. The composition of pyrolysis products depends on the type of waste input and can vary significantly, but generally consists of:

- **Solid:** A char-like substance containing residual solid materials such as sand, glass, and metals, as well as some ashes.
- **Liquid:** A complex mixture of hydrocarbons, including organic acids, phenols, PAHs, and alcohols, composed of water, tar, and oil. This accounts for the largest fraction of pyrolysis products, namely py-oil.
- **Gas:** A mixture of CH_4, C2's, C3's, CO_2, and other volatile waste constituents (HCl, N-species, S-species).

The reactors used for pyrolysis include rotary kiln or auger reactors, as well as continuous stirred-tank reactors.

The products of pyrolysis are only intermediate products. Further refining is necessary before they can be processed similarly to naphtha. Pre-treatment and upgrading are essential, usually involving hydrotreating (removal of heteroatoms and stabilisation), fractionation/distillation and sometimes catalytic treatment to adjust the hydrocarbon profile. Only after such steps can a portion of the upgraded oil be co-fed into steam crackers within certain blend ratios to protect process stability and product quality.

The standard process can be modified in various ways to change the reaction conditions and, consequently, the resulting products, as described below.

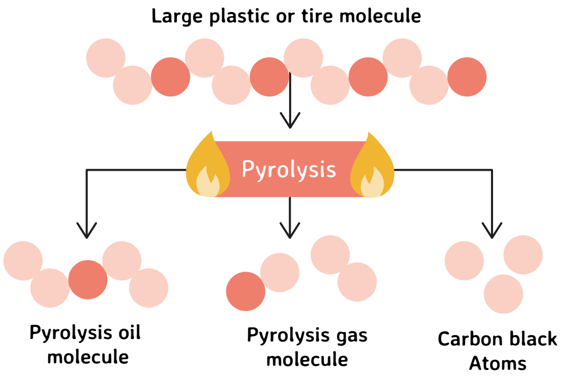


Figure 54: Different pyrolysis products.

• Non-Catalytic Pyrolysis

Non-catalytic pyrolysis, also known as thermal pyrolysis or thermolysis, does not involve the use of a catalyst. The plastic waste is heated to high temperatures in an inert atmosphere, causing the polymer chains to break down into smaller molecules. This process produces a mixture of gases, liquids, and solid residues. The products can be further refined into chemicals and fuels. To decrease the reaction times and reach higher conversion rates, thermal plasma or microwave energy can be applied for heating.

• Catalytic Pyrolysis

Catalytic pyrolysis involves the use of a (heterogeneous) catalyst (like silicate zeolites, metal oxides or cobalt complexes) to lower the temperature required for the pyrolysis process and to improve the yield and quality of the products, in the absence of other compounds like oxygen[40]. The plastic waste is heated in the presence of a catalyst, which facilitates the breakdown of the polymer chains into smaller hydrocarbons. This method can produce high-quality chemicals and fuels with greater efficiency.

Hydrogen-assisted plastic conversion

Hydrogen-assisted plastic conversion refers to thermocatalytic processes like hydrogenolysis, hydrocracking, and hydrothermal liquefaction (HTL), where hydrogen helps break down polymers into smaller, stable hydrocarbons.

Hydrogenolysis involves cleaving C–C bonds in plastics (e.g. PE, PP, PS) using hydrogen and metal catalysts (e.g. Ru, Pt) at moderate temperatures (250–350 °C) and low hydrogen pressures. This process produces saturated hydrocarbons with minimal gas or char.

The **hydrocracking** process is used to transform heavy, high-boiling plastic molecules into lighter, low-boiling molecules[41]. It uses higher hydrogen pressures (3–15 MPa) and bifunctional catalysts that combine hydrogenation and acid-cracking functions to convert mixed plastic waste into fuels and naphtha-range products. Hydrogen in these processes serves multiple purposes, like saturating double bonds to prevent secondary reactions, suppressing char formation and removing heteroatoms like sulphur, nitrogen, oxygen, and halogens via hydrodesulfurization, hydrodenitrogenation, etc.

HTL with hydrogen operates in supercritical water (150–400 °C, 20–35 MPa) and can process wet, contaminated waste. Hydrogen, which is either added or released from donor molecules, improves product quality and reduces char. HTL is well-suited for wet and contaminated plastic waste, including food-soiled and multilayer packaging, as it does not require feedstock drying. The use of supercritical water enables efficient heat transfer, reducing char formation compared to pyrolysis.

Gasification

Gasification involves the partial oxidation (with a controlled amount of oxygen) of plastic waste at high temperatures with a gasifying agent (e.g., steam, oxygen and air) to produce syngas, which is a mixture of light hydrocarbons, hydrogen, carbon monoxide, methane and other gases[42]. Through a water-gas shift reaction, gasification can be led to maximise CO or H_2 yields.

Generally, gasification produces three types of outputs:

- **Gas:** The primary product of gasification is syngas, which is a mix of CO and H_2 with varying contents of CO_2 and smaller amounts of CH_4.
- **Solid:** Ashes containing non-volatile metals and other inorganic elements.
- **Liquid:** Smaller quantities of oil and tar.

The aim of plastics gasification is to maximise the conversion of plastic waste into syngas or gas products while minimising the production of char and tar, which are undesirable by-products. Gasification is a complex process involving numerous chemical reactions[43]. The produced syngas can be used as a fuel or as a feedstock for the production of chemicals and other valuable products. Syngas can serve as a precursor to synthetic natural gas, though it has a lower energy content compared to natural gas. It can also be used to produce chemical feedstocks like ethanol, methanol, and ammonia. However, converting syngas into new plastic precursors requires extensive processing, which is why this technology is rarely used for plastic remanufacturing. Commercially, gasification and subsequent conversion to methanol is often used to liquify stranded natural gas or for energy recovery by generating heat or electricity from syngas. Stranded natural gas refers to natural gas reserves that are not economically viable to transport via pipelines. Gasification and subsequent methanol production provide a solution by converting the gas into methanol, which is easier to transport and utilise.

Plastic waste gasification processes are similar to those for coal and biomass, but the unique properties of plastics, such as high volatility, thermal resistivity, stickiness, and high tar production, pose challenges. Effective gasifier designs for plastics must ensure high heat transfer rates for rapid depolymerisation, tightly controlled operating conditions to manage stickiness, and sufficient residence time to crack tar and maintain good contact with in-situ catalysts.

Chemical Depolymerisation

What: Chemical depolymerisation (also referred to as: chemolysis, solvolysis) is a process that breaks down polymers into their monomeric or oligomeric components, using a depolymerisation reacting agent, making them suitable for repolymerisation into new plastics.

How: This process involves various chemical reactions that target the polymer chains, breaking them down into shorter chain oligomers (partial depolymerisation) or the monomers from which it was formed (full depolymerisation). The main techniques used in chemical depolymerisation include solvolysis, using a reacting agent. Once depolymerisation has occurred, the monomers are recovered and purified through distillation, precipitation, or crystallisation processes to remove contaminants, resulting in pure monomers. These recycled monomers can be of the same quality as the original raw materials, regardless of the polymer grades in the waste plastic. The reacting agent can also be purified downstream and recycled in a closed loop.

Chemical depolymerisation is feasible for certain plastics, such as PET, other polyesters, Polyurethane (PU), Polyamides (PA), and Polylactic Acid (PLA). These are known as condensation polymers due to their formation process. Suitable chemicals for depolymerising other (condensation) polymers have not yet been discovered.

Polymerisation of plastics occurs via two routes:

1. **Addition Polymerisation:** Monomers with multiple bonds form carbon-carbon bonds.
2. **Condensation Polymerisation:** Monomers bond by ejecting a small molecule (often water). This usually includes the presence of a functional group, like an ester group, as shown in Figure 55.

Condensation polymers, like PET and PA, have reactive bonds (e.g., ester bonds), also called a functional group, that facilitate depolymerisation by reintroducing the small molecule lost during polymerisation. Depolymerisation involves breaking the bonds between monomers. The specific reaction pathway depends on the small molecule used in the process. As described below, there are a few main chemical inputs, each leading to a different monomer output.[44]

Solvolysis

- **Glycolysis:** In glycolysis, glycols are used to depolymerise the plastic. The process involves heating the polymer with a glycol, leading to the breakdown of the polymer into smaller units. Glycolysis is a specific type of alcoholysis, where glycols (a subset of alcohols) are utilised to achieve the depolymerisation.

- **Methanolysis:** Methanolysis uses methanol to depolymerise the polymer. The polymer is heated with methanol, causing it to break down into its monomeric components. By this method, virgin-like DMT and ethylene glycol are obtained, which are the building blocks for the production of polyester. Therefore, these monomers can be used in original polyester polymerisation processes, for example.

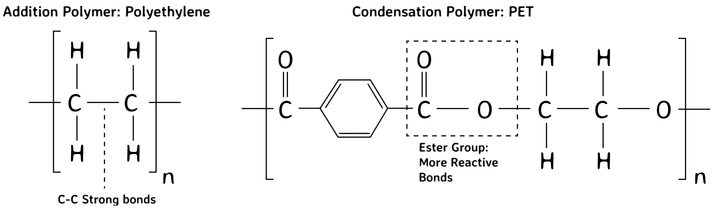


Figure 55: two polymers following different polymerisation routes[45].

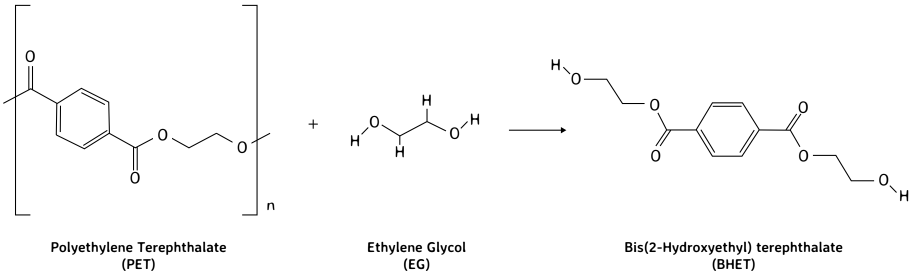


Figure 56: Chemical reaction of PET glycolysis.

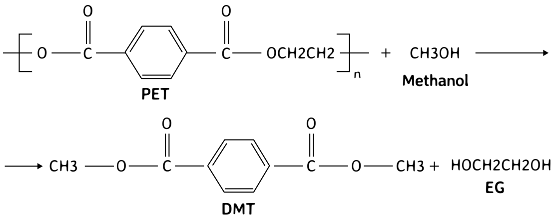


Figure 57: Chemical reaction of PET methanolysis.

- **Aminolysis:** This method involves the use of ammonia or an amine to break down the polymer chains. The reaction with amines results in the formation of smaller molecules from the polymer.

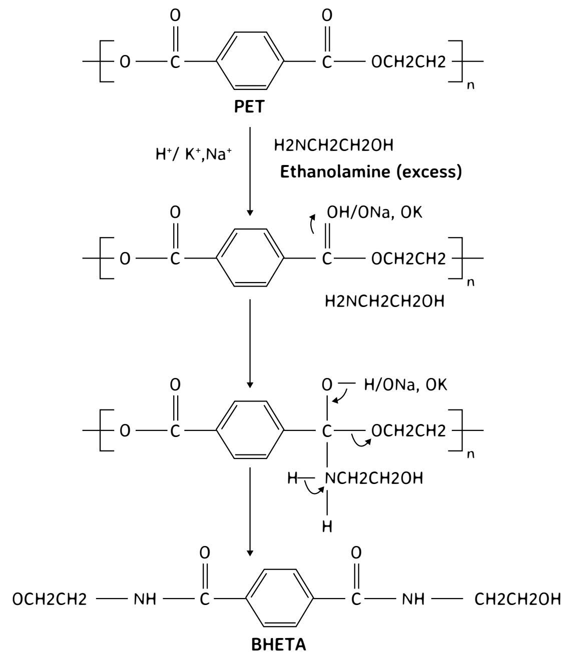


Figure 58: Chemical reaction of PET amminolysis.

- **Ammonolysis:** This method involves the use of ammonia to break down the polymer chains. The reaction with amines results in the formation of smaller molecules from the polymer.

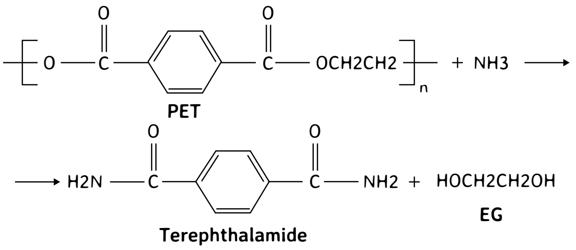


Figure 59: Chemical reaction of PET ammonolysis.

Hydrolysis

- **Non-Catalytic Hydrolysis:** This technique involves breaking down the polymer using water without the aid of a catalyst. The process typically requires high temperatures and pressures to achieve effective depolymerisation.

- **Catalytic Hydrolysis:** In catalytic hydrolysis, a catalyst is used to accelerate the reaction between the polymer and water. This method is generally more efficient and can occur at lower temperatures and pressures compared to non-catalytic hydrolysis.

The mechanism for hydrolysing PET, whether in acidic/neutral or alkaline conditions, involves breaking the ester linkages in the main chain using H+ or OH-. This process results in the formation of one carboxyl end group (TPA) and one hydroxyl end group (EG).

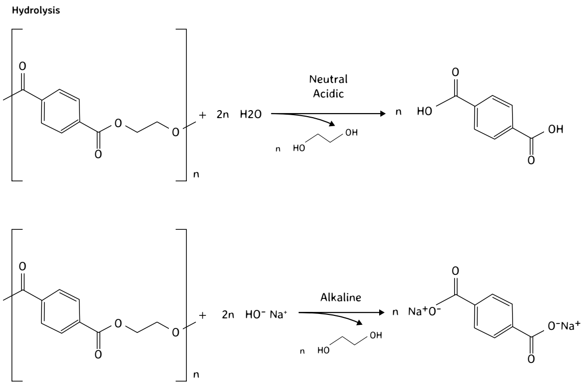


Figure 60: Chemical reaction of PET hydrolysis.

- **Enzymatic depolymerisation:** This hydrolysis technique uses specific enzymes to break down the polymer chains. These enzymes specifically target the polymer bonds, resulting in the formation of monomers or oligomers. This method operates under milder temperatures and pressures compared to chemical methods. However, sulfuric acid and caustic soda are used to precipitate the TPA, resulting in a relatively high consumption of chemicals and water.

Detailed information on process yields, chemical inputs, and purification methods is often lacking. Technologies vary in their use of catalysts and reacting agents, with some designed for reuse. Process conditions also differ, with some operating at low temperatures and others using higher energy inputs to reduce reaction times.

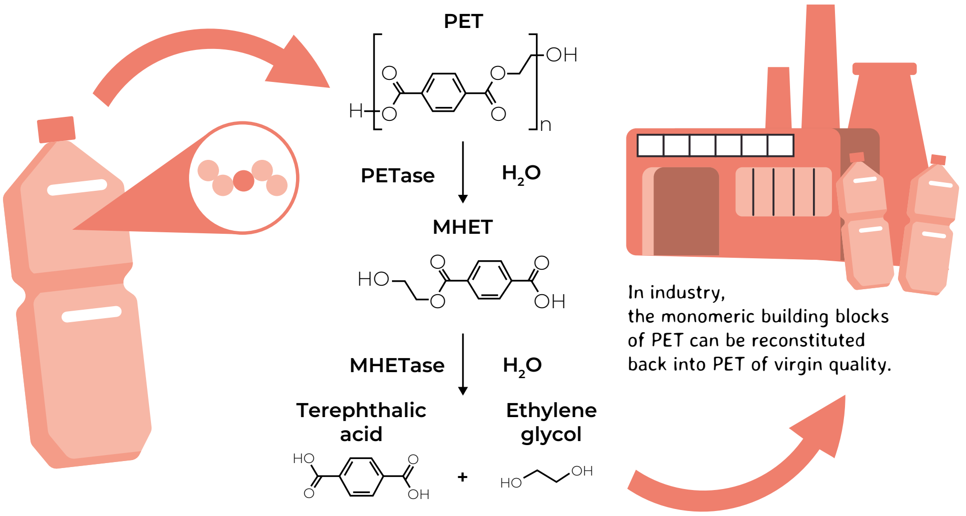


Figure 61: Chemical reaction of enzymatic PET hydrolysis.

Overall, the long-term viability and commercial success of these chemical recycling technologies remain uncertain from both environmental and economic perspectives[46].

An important note about chemical depolymerisation is that, contrary to thermal degradation, no fuel is produced.

Catalysts are essential in these pathways, speeding up reactions by interacting with the materials. For example, hydrolysis is slow and often incomplete without a catalyst. Catalysts, such as ionic liquid complexes or enzymes, are specifically developed for these processes but can be costly and require separation from the monomer products afterwards.

Other methods to enhance depolymerisation and decontamination include using specific reacting agents and process conditions. Reacting agents improve mixing but can be toxic and impractical on an industrial scale. Temperature and pressure can reduce reaction times but increase energy consumption, impacting both environmental and economic factors.

Chemical depolymerisation has garnered significant attention for its ability to degrade polymers and purify monomers. Various technologies produce commercial outputs, primarily using monomers to create recycled yarns for textiles. Most focus on polyester-rich waste, though some focus on less recyclable materials like pigmented packaging or food trays. There are fewer commercial-scale technologies for PU, PA, or PLA.

The main challenge in scaling up chemical recycling lies in securing a consistent and adequate feedstock supply. While bottle-to-bottle mechanical recycling is well established for clear PET, other streams like textiles and flexible packaging lack efficient mechanical solutions. Chemical recycling aims to address these gaps by processing waste streams that currently have no viable alternative. However, transitioning from lab-scale operations, which handle small quantities, to full-scale industrial processes requires a well-structured supply chain. Key considerations include whether to receive feedstock pre-shredded, how to manage storage logistics, and how to ensure a steady input of suitable material to maintain continuous operation. By addressing these challenges, chemical recycling can complement existing recycling methods and provide a solution for hard-to-recycle plastics.

Purification

The purification step in chemical recycling is crucial yet often under-detailed across various technologies. Indeed, there is a general lack of clarity on how contaminants are managed post-purification, and the level of contamination that these technologies can handle remains uncertain.

In **thermal decomposition** processes, the purification of pyrolysis oil before it enters the steam cracker is critical to meet strict feedstock specifications, as contaminants can reduce efficiency and equipment lifespan. Indeed, most chemical recycling technologies are resilient to contaminants such as PET and, to some degree, PVC and their degradation products, whereas steam crackers are not.

Purification is necessary to make the produced oil suitable for use in monomer-producing steam crackers (as a naphtha substitute). Efficiency losses will occur in the cracker because the conversion efficiency of untreated pyrolysis oil is different from that of virgin hydrocarbon feedstocks. This is crucial since steam cracker inputs may include a mix of pyrolysis oil and virgin hydrocarbons, making the relative contribution to the output monomer different and only theoretically calculable rather than directly measurable[47].

Processing mixed plastic waste can produce hazardous by-products like toxic polycyclic aromatic hydrocarbons and dioxins. PVC and other halogen-containing wastes (e.g., chlorine, bromine) are particularly problematic, as their breakdown generates acidic gases like hydrogen chloride, which are corrosive and can damage equipment. Extensive purification is needed to remove these contaminants.

In some cases, the purification step is not necessary in pyrolysis because only very small amounts of the py-oil are added in the cracker. Such blending makes it very diluted with the regular (virgin) feedstock, lowering the concentration of potential remaining impurities to acceptable levels.

Additionally, the purification process required to produce fuel-grade material is relatively simple compared to isolating chemical feedstocks. This simplicity, combined with the high costs of converting feedstocks into high-value materials and the nascent state of recycled chemical supply chains, has often locked the thermal degradation technologies into plastics-to-fuel pathways rather than true recycling. Elimination of contaminants like oxygenates or nitrogen compounds is a challenge.

In **chemical depolymerisation** processes, purification involves the recovery of catalysts, reacting agents and the final monomers, usually by using multiple techniques like filtration, distillation, crystallisation and washing. After initial depolymerisation, unreacted materials are filtered out, and the resulting monomers undergo further decontamination and purification to ensure a clean product. This process includes the recovery of chemical catalysts and reacting agents for reuse. For instance, some technologies employ a separate catalyst and pigment adsorbent, combined with a selective purification process, to recover both monomers and catalysts.

An important note is that whereas chemical depolymerisation delivers the final monomers that are the original building blocks for plastic material after the purification steps, in the case of thermal decomposition, the obtained pyrolysis oil or syngas is sent to a steam cracker before obtaining the final monomers. These crackers are usually existing assets in which the recycled oil or gas is mixed with a fossil-derived feedstock.

As can be seen in Figure 62, after re-polymerisation of the monomers, the obtained product derived from chemical recycling is clean, in the form of transparent granulates, which are suitable for highly regulated applications such as food packaging or medical applications.

Figure 62: Re-polymerised granulates.

Quality Control

Ensuring the quality and safety of recycled materials is paramount in chemical recycling processes, including both chemical depolymerisation and thermal degradation. For pyrolysis, specific attention is given to the presence of substances of very high concern SVHC's in the pyrolysis oil. According to recent studies, various SVHCs can be found in the pyrolysis oil derived from plastic waste, and these substances may also form during the pyrolysis process.[48]

To maintain high standards, the following quality control measures should be implemented:

1. **Regular Monitoring:** Conduct frequent analyses to detect and quantify SVHCs in the process products and by-products. This includes both pre-treatment and post-treatment stages to ensure that any harmful substances are effectively removed.
2. **Compliance with Regulations:** Adhere to legal requirements and guidelines for the safe handling and disposal of SVHCs.
3. **Transparency and Data Sharing:** Encourage transparency by sharing data on SVHC concentrations with relevant stakeholders.

In chemical recycling, quality control also ensures that the resulting monomers and chemicals meet reuse standards. This involves feedstock analysis of incoming plastic waste, process monitoring of depolymerisation and thermal decomposition conditions, and product purity testing of the final products. Ensuring minimal residual contaminants is essential, especially for high-purity applications. These measures help produce high-quality, reusable materials that comply with regulations.

Chemical Recycling Technologies

In this section, the modules mentioned in the previous chapter, such as *preparation steps, chemical depolymerisation, thermal decomposition* and *purification* will be further elaborated according to the different types of plastic waste streams treated for recycling. For each stream, the basic modules have been kept and complemented by adding some sub-units when necessary to ensure the most complete level of detail. Specific recycling technologies are highlighted in the following colours: dark green corresponds to a technology widely employed in the plastic recycling industry, light green represents a technology with a medium level of implementation, yellow corresponds to a technology with low level of implementation, orange refers to technologies which are currently under development and used by very few recyclers at the industrial scale.

In this section, PO pyrolysis and Polyester depolymerisation will be further explained, as these are currently the two main technologies where most investment capacity is planned in the chemical recycling industry.

PO Stream

PO waste can be chemically recycled through thermal decomposition in an oxygen-free system. The pre-treated plastic waste is converted to a hydrocarbon mixture that can partially be used as feedstock for liquid steam crackers or refineries.

The flowchart for the pyrolysis of PO waste is shown in Figure 63. The gas and char fractions are included in the chart as they can be used as fuel or feedstock for (lower quality) material.

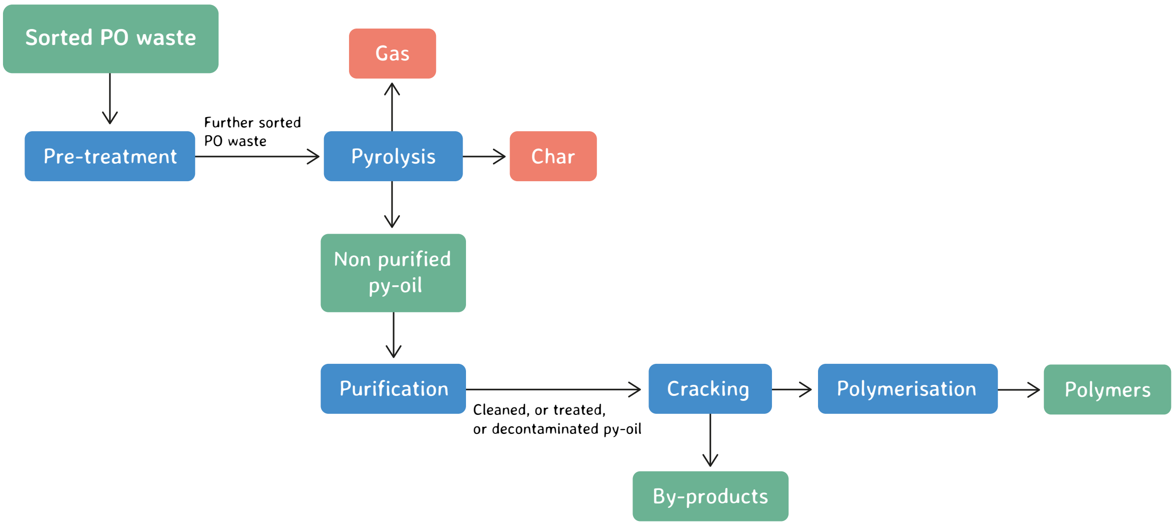


Figure 63: Process flow - pyrolysis of PO sorted waste.

Recycling of Polyolefins via Thermal Decomposition

Thermal degradation of polyolefins involves several steps to convert waste plastics into valuable products. Below is an overview of each step, including operating conditions and industrial applications.

Steps:
1. **Pre-treatment**
2. **Pyrolysis / Gasification / Hydrogen-assisted plastic recycling**
3. **Purification**

1. Pre-treatment: collection and sorting

Pre-sorting

Bales of mixed plastic waste, primarily polyolefins (PO), arrive at recycling facilities in varying conditions, often containing contaminants such as PVC, PET, metals, and organics. While sorting is initially done at collection centres, additional pre-sorting is often required before recycling. This process typically includes grinding, magnetic separation, and near-infrared (NIR) sorting, depending on the recycling line.

Facilities process mixed PO-rich waste and municipal solid waste (MSW), using front-end sorting and drying to remove contaminants before feeding agglomerated material into an extruder and reactor. The focus is on pre-sorted post-consumer flexibles, removing PVC, PET, and polyamides to meet pyrolysis specifications. Contaminants such as chlorine, oxygen, and nitrogen are particularly problematic, as they impact pyrolysis oil quality and downstream steam cracking. While some facilities extrude waste into pellets, others prefer shredded or agglomerated forms for easier transport and processing. The extent of sorting versus purification remains a key optimisation question in chemical recycling. The feedstock entering PO recycling facilities can be in the form of filter residue from mechanical recycling, agglomerates or flexible polyolefin flakes.

2. Recycling technologies

Thermal pyrolysis

Pyrolysis involves the thermal decomposition of polyolefins in the absence (or near absence) of oxygen to produce smaller hydrocarbons. The process generates pyrolysis oil, gases, and char, which can be further refined into fuels and chemicals.

Operating Conditions:

- **Temperature:** 400-700 °C
- **Atmosphere:** Inert (e.g., nitrogen) or low oxygen

Agglomerates or extrudates that are melted into liquids enter the reactor (which can be a continuous, semi-batch or batch stirred reactor) at a temperature of around 300 °C. The reactor is heated further as the pyrolysis reaction takes place at temperatures above 400 °C, yielding a pyrolysis oil consisting of a mix of smaller polymer chains. In these cases, non-condensable gases produced during the reaction can be used to sustain energy needs, enhancing process efficiency. The residence times can vary between 30 minutes and 12 hours, depending on the type of reactor, volume, temperature and other process parameters.

Scaling up, however, presents challenges due to waste buildup, and char disposal remains an issue, though it can be suggested as having potential applications such as asphalt production. Another significant challenge in pyrolysis remains efficient heat transfer, as molten plastics have poor heat conductivity but need to reach a certain temperature in order to react. This issue is often mitigated using heat carriers such as sand, water, silicon carbide (SiC), and other materials.

Catalytic pyrolysis

Catalytic pyrolysis is a variation of pyrolysis that incorporates a (heterogeneous) catalyst, typically a zeolite, to lower reaction temperatures and enhance product quality. The process generates pyrolysis oil, gases, and char, which can be further refined into fuels and chemicals. The residence time typically ranges from 30 minutes to two hours, depending on process conditions.

Operating Conditions:

- **Temperature:** 400-500 °C
- **Atmosphere:** Inert (e.g., nitrogen) or low oxygen
- **Catalyst:** zeolite

Similarly to thermal pyrolysis, achieving a homogeneous heat distribution that allows all plastics to crack to shorter polymer chains is a challenge. Both pyrolysis oils from catalytic and thermal pyrolysis can be sent to steam crackers that are used for the production of virgin polymers as well. These steam crackers can be fed a mix of pyrolysis oil and virgin feedstock oil. Some companies that have large facilities can actually acquire pyrolysis oil from a smaller chemical recycler, as well as feed their own pyrolysis oil if they have a recycling facility too.

Gasification

Gasification is a high-temperature thermal decomposition process that converts plastic waste into syngas (a mixture of CO, H_2, and CH_4) in a controlled, oxygen-limited environment. Unlike pyrolysis, gasification produces more gaseous outputs than liquid hydrocarbons.

Contamination from PVC and other halogenated plastics necessitates additional purification steps to remove hazardous compounds such as hydrogen chloride. Advanced gas-cleaning systems are required to filter out tars, particulates, and corrosive gases to ensure a clean syngas output suitable for industrial use.

Operating Conditions:

- **Temperature:** 700-1200 °C
- **Pressure:** 2-5 MPa

Despite its potential, gasification faces several challenges. Contaminant removal remains a critical issue, as halogens and sulphur compounds must be effectively scrubbed to prevent equipment corrosion and environmental emissions. Additionally, the purification of syngas requires efficient filtration to remove impurities, ensuring its usability in downstream applications. The high energy demands of gasification necessitate robust energy recovery strategies, often leveraging a portion of the generated syngas for self-sustaining operation.

Hydrogen-assisted plastic conversion

HTL with hydrogen is a hydrothermal decomposition process that occurs in a high-pressure, water-rich environment. The incoming plastic can be shredded before being melted and pressurised by an extruder. It is then mixed (at around a 1:1 ratio, with some margin) with supercritical water and further heated to enter the reactor. Inside the reactor, plastics are transformed into liquid hydrocarbons and gas, where the residence time can be as little as 30 minutes. After the conversion process, the pressure is released. The energy recovered during this stage can then be utilised in the subsequent phase, which involves product separation into individual fractions.

Operating Conditions:

- **Temperature:** 150-400 °C
- **Pressure:** 20-35 MPa
- **Catalyst / anti-acid:** If any, can be heterogeneous (powder / solid catalyst) or a homogeneous anti-acid solution (aqueous solution of sodium hydroxide, for example) to abate hydrochloric acid and reduce corrosivity risk.

Unlike conventional pyrolysis, hydrothermal recycling does not require complete drying of feedstock, making it particularly suitable for wet waste streams, including plastics mixed with organic materials. The resulting oil can be further refined into fuels and valuable chemical feedstocks. While hydrothermal conversion presents advantages in handling mixed waste streams and reducing energy-intensive drying steps, challenges remain in optimising reaction conditions, scaling up reactor designs, and managing aqueous by-products containing dissolved contaminants.

3. Separation and purification technologies

The purification process in chemical recycling is essential for removing atomic impurities and unwanted by-products from cracked hydrocarbons to isolate the desired hydrocarbons. This can involve several steps, including basic separation methods like condensation or distillation and hydrotreatment, as detailed below.

Purification is necessary before entering the steam crackers, as they are sensitive to contaminants. Indeed, naphtha specifications are needed for those steam crackers. As they are usually fed with naphtha, no steam crackers specifically installed for chemically recycled pyrolysis oil have been reported as of today. This means that all sorts of heteroatoms like nitrogen, metals, phosphor, silicium and sulphur must be removed. This contrasts with the chemical recycling reactors that themselves are quite robust to contamination.

Condensation

The condensation step in the purification process involves cooling vaporised hydrocarbons to separate liquid fractions from the gas. This is typically achieved through simple condensation steps, where the temperature is lowered to condense the vapor into liquid form. The primary goal is to isolate the desired liquid hydrocarbons from the gaseous by-products.

Distillation

Distillation is a method that separates molecules based on their boiling temperature by using a distillation tower with different temperatures at different heights or plates. In the context of chemical recyclates, it allows for the separation of a bottom fraction, which can be used for bitumen production, and other, lighter fractions, which can be used in a naphtha cracker (for the production of plastics material feedstock, amongst others).

Hydrotreatment

Hydrotreatment is a critical purification method where hydrogen reacts with impurities such as sulphur, nitrogen compounds and oxygenates. The crude pyrolysis oil is hydrogenated in the presence of an organic hydrogen donor, mostly with H_2 gas, and a heterogeneous catalyst to obtain hydrogenated crude pyrolysis oil, which includes hydrocarbons and hydrogenated impurities. These impurities are converted into stable compounds like H_2S, NH_3, and H_2O, which are removed from the product stream by phase separation, gas stripping, or distillation.[49] Being a continuous process, the hydrotreatment is advantageous for industrial applications. The hydrotreatment step upgrades the pyrolysis oil to a naphtha-quality feedstock suitable for steam crackers, producing monomers like ethylene and propylene. This treatment is very selective in removing the heteroatoms. It is also used in the refinery industry, with gasoil refiners operating under similar conditions.

Other, less commonly used purification methods include the use of hexane or other solvents to extract specific fractions, such as light olefins or aromatic hydrocarbons.

Overall, the purification process must be optimised to handle the random nature of thermal decomposition of plastics, which produces a complex mixture of products. This requires costly purification systems to isolate usable products, making the process more challenging compared to producing fuel-grade material. Despite these challenges, the purification step is crucial for ensuring the quality and viability of the recycled chemical feedstocks.

Important Note: After the initial extraction and depolymerisation steps, additional processes such as steam cracking and other conventional methods are essential to complete the transformation into usable polymers. These subsequent steps involve breaking down the smaller hydrocarbon molecules further and refining them to produce high-quality monomers. These monomers are then (re-) polymerised to create new polymers, ready for various applications in manufacturing and industry.

Polyester Stream

Polyester (PES) waste can be chemically recycled by depolymerisation, a process where the chemical structure of a polymer is broken down to obtain monomers and oligomers.

With the mechanical recycling of PET bottles being well-established and highly competitive, efforts are directed towards other material streams that lack adequate recycling solutions, such as polyester fibre (textile), pigmented packaging and food trays. The flowchart for the chemical depolymerisation of polyester waste is shown in Figure 64.

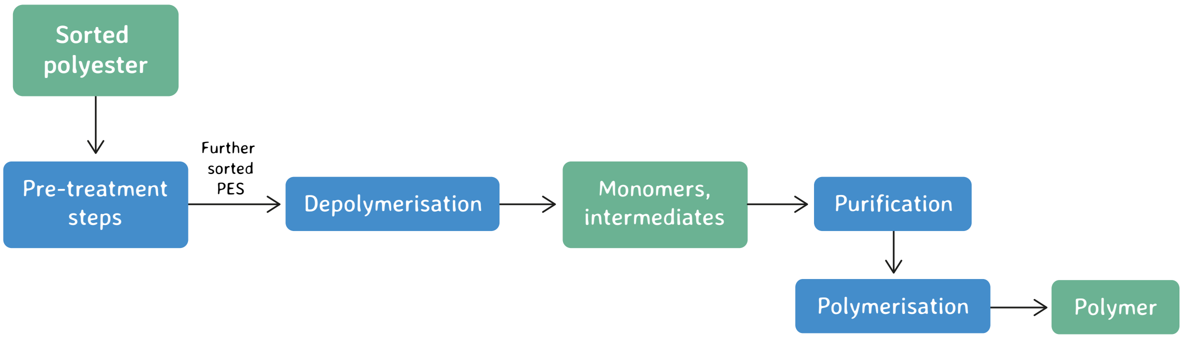


Figure 64: Process flow – depolymerisation of PES.

Recycling of Polyesters with Chemical Depolymerisation

Chemical depolymerisation of polyester involves several steps to convert waste plastics into valuable products such as dimethyl terephthalate (DMT), terephthalic acid (TPA), bis(2-Hydroxyethyl) terephthalate (BHET) and ethylene glycol (EG). These processes break down the polyester chains into their monomer components, which can then be purified and reused in the production of new polyester materials. DMT, TPA and BHET are key intermediates in the synthesis of polyesters, while EG is a valuable byproduct used in various industrial applications. This method not only helps in the recycling of polyester waste but also contributes to a more sustainable and circular economy by producing high-purity monomers for recycling. Below is an overview of each step, including operating conditions and industrial applications.

Steps:

- **Pre-treatment**
- **Methanolysis / Glycolysis / Hydrolysis**
- **Purification**

Pre-treatment: collection and sorting

Pre-sorting

For complex waste streams, such as mixed PET and polyester-based materials, chemical recycling can offer an advantage over mechanical methods by eliminating the need for extensive pre-sorting. For most systems, achieving a certain degree of purity is essential to maintain process efficiency and maximise yield. Typically, input materials should contain at least 80 % PES (PET or textiles), with most chemical recycling facilities further purifying them up to 95 % purity. While these bales can be sourced from mechanical recyclers and waste management partners, additional simple preparation steps are often necessary at chemical recycling facilities, including washing, sorting, and size reduction. These processes typically include grinding, magnetic separation, or near-infrared (NIR) sorting, depending on the recycling line. Contaminants such as non-targeted plastics, especially nitrogen-containing ones (e.g., polyamides, PVC), can be problematic in catalytic processes, as they can negatively affect the reaction.

With certain processes, however, it is possible to handle unsorted post-consumer or post-industrial waste, including multilayer packaging and multi-coloured textiles, without requiring prior washing or separation of non-polymer components. Some advanced but not yet widely implemented systems can tolerate the presence of non-recyclable or non-targeted materials such as polyolefins, adhesives, and paper, which remain intact during processing and are removed through post-reaction filtration. In that case, only physically disruptive elements, such as large metal pieces or stones, must be removed beforehand. Feedstock preparation in such cases is minimal, typically involving shredding or grinding to facilitate uniform mixing and prevent material from adhering to reactor walls. However, less recycled output results in lower yields, so more sorting improves yields and overall viability.

Recycling technologies

Chemical recycling of polyesters involves breaking down the polymers into the monomers or other valuable chemicals, enabling the production of new PET or other materials. The primary chemical recycling processes that are implemented industrially for polyesters include:

1. **Glycolysis**
2. **Methanolysis**
3. **Hydrolysis**

Below is an overview of each process, its operating conditions, and the corresponding implementation status:

Glycolysis

Glycolysis involves reacting PET with glycols, such as ethylene glycol, to produce bis (2-hydroxyethyl) terephthalate (BHET) monomers. These intermediates can be repolymerised to form PET or utilised in other applications.

In this process, post-consumer polyester is generally washed and ground into flakes for rapid dissolution before being added to the glycolysis reactor with glycol. In a continuous process, the polyester oligomer/monomer in the reactor reacts to depolymerise high molecular weight polyester flakes, allowing the glycolysis reaction to proceed quickly. Transesterification catalysts like Mn, Zn, Sb, Ti, Sn, or Ge salts can be used to increase the glycolysis yield. The correct glycol-to-polyester ratio is crucial to ensure the reaction mixture's viscosity allows low-density contaminants to migrate away from the polyester. During glycolysis, low-density contaminants can be separated from the polyester while still in the reactor by siphoning, vacuuming, absorbing, or skimming. High-density contaminants, which are insoluble and larger than about 50 microns, can be filtered out of the mixture.

Operating Conditions:

- **Temperature:** 150-300 °C
- **Atmosphere:** 0.05 – 0.5 MPa
- **Catalysts:** If any, transesterification catalysts

Methanolysis

In methanolysis, two steps can usually be identified:

- **Treating Step (Depolymerisation):** The polyester is treated with methanol in stoichiometric excess, and in the presence of some other solvents depending on the process. Through the aid of a catalyst, the methanol selectively breaks the polyester down into dimethyl terephthalate (DMT) and diols (like ethylene glycol).
- **Converting Step:** After the depolymerisation, the diols produced are converted into non-reactive compounds. This step is crucial to prevent any unwanted side reactions that could affect the quality and stability of the DMT.

Both steps can be performed in a depolymerisation reactor and form a flowable reaction product mixture including DMT, EG, methanol, residual polyester, and other products, depending on the process. The treating step and the converting steps can happen simultaneously and at the same process conditions.

Operating Conditions:

- **Temperature:** 150-300 °C
- **Atmosphere:** 0.5 – 40 MPa
- **Catalysts:** One or more basic compounds

Hydrolysis

Hydrolysis involves breaking down PET using water (neutral hydrolysis), acids (acid hydrolysis), bases (alkaline hydrolysis), or enzymes (enzymatic hydrolysis) to yield terephthalic acid (TPA) and ethylene glycol, usually at high temperatures and pressures.

The main current methods for PET hydrolysis require high temperatures (200-350 °C) and pressures (>1 MPa). Neutral hydrolysis of PET at room temperature is minimal due to its insolubility in solvents like water and ethanol. However, combining these solvents with an acid or base initiates depolymerisation over time. The hydrolysis mechanism, whether acidic/neutral or alkaline, involves breaking the ester linkages in the PET main chain via H+ or OH-, resulting in one carboxyl end group (TPA) and one hydroxyl end group (EG). Alkaline hydrolysis typically uses NaOH or KOH solutions (4-20 wt. %). Recent innovations using metal-UV light and photocatalysts have developed low-temperature, low-pressure hydrolysis technologies that avoid harsh processing conditions, being able to take place under ambient conditions. Post-reaction, the medium consists of a solid stream (requiring purification and crystal growth for TPA separation) and a liquid stream (requiring purification and distillation to recover MEG).

Operating Conditions:

- **Temperature:**
  - High-temperature methods: 200-350 °C
  - Low-temperature innovations: Ambient conditions
- **Pressure:**
  - High-pressure methods: >1 MPa
  - Low-pressure innovations: Ambient pressure
- **Solvents:**
  - Neutral hydrolysis: Water, ethanol (minimal effect at room temperature)
  - Acidic/alkaline hydrolysis: Water or ethanol combined with acid or base
- **Catalysts:**
  - None, Metal-Organic Frameworks, zeolites, or photocatalysts like TiO2

In enzymatic hydrolysis, biological recycling processes typically involve placing plastic waste in a bioreactor with specific enzymes of classes like PETase and MHETase, which bind to PET polymers and monomers to depolymerise the long PET chains. As enzymes only attack the amorphous phase of PET and as PET is a semi-crystalline polymer, PET must be amorphised before the enzymatic hydrolysis takes place. In some cases, intermediate enzymes may be used to produce or activate molecules that depolymerise the plastic into monomers. Recombinant microorganisms expressing and excreting these enzymes can also be employed, with modifications to prevent the consumption of resulting monomers. In general, the temperature is kept below the inactivation temperature, which is the point at which the enzyme becomes inactive, or the microorganism stops producing the degrading enzyme. Reaction times of about ten hours are expected for enzymatic hydrolysis.

Separation & purification technologies

After depolymerisation, the resulting monomers or oligomers often contain impurities and contaminants. These need to be removed to ensure the quality of the final product. Separation and purification methods can include:

- **Distillation:** Separates components based on boiling points. Mainly used for separating DMT and MEG.
- **Filtration:** Removes solid impurities. Mainly used for separating BHET and TPA.
- **Extraction:** Uses solvents to separate desired compounds from impurities.

More specifically, in the case of polyester recycling, the following steps are applied industrially:

Glycolysis

Glycolysis involves breaking down PET using glycols, such as ethylene glycol, to produce bis(2-hydroxyethyl) terephthalate (BHET) monomers or oligomers. The purification of these products is crucial to ensure high-quality recycled PET (rPET). The main purification steps include:

Separation of reaction by-products

- Excess glycol is removed through vacuum stripping at temperatures below 200 °C to recover the unreacted glycol for reuse.
- Solid impurities, such as pigments and fillers, are removed via filtration (typically through membranes or activated carbon filtration).

Solvent purification

- The reaction mixture is dissolved in a hot solvent, such as water or an ester-based medium, to facilitate the separation of impurities.
- Large molecular weight contaminants and unreacted polymer fragments are removed by flotation, filtration, or centrifugation.

Crystallisation and precipitation

- The purified BHET solution is gradually cooled, leading to the precipitation of BHET crystals.
- These crystals are washed with solvents (e.g., methanol or water) to remove residual contaminants.

Final processing

- The recovered BHET monomers are dried and stored for repolymerisation into new PET products.
- Any remaining polymeric residues are thermally treated or subjected to additional purification steps before reuse.

Methanolysis

As mentioned in the depolymerisation part of methanolysis, a flowable reaction product mixture including DMT, EG, methanol, residual polyester, and other products, depending on the process that is selected by the recycler. The most important (valuable) product to separate from this mixture is DMT. The purification steps include:

- **Vaporising:** By heating the product mixture, by lowering the pressure, or by adding a stripping agent as a low-boiling solvent.
- **Distillation:** To separate methanol and other volatile impurities.
- **Crystallisation:** Cooling the reaction mixture until DMT is crystallised from the solution and purified by recrystallisation or distillation.
- **Filtration:** To remove any remaining solid impurities.

Hydrolysis

Hydrolysis can be acidic, basic, or neutral, producing terephthalic acid (TPA) and ethylene glycol. Purification involves:

Membrane filtration: To remove solid impurities (at room temperature). Some recent innovations allow for non-pre-sorted waste to enter the reactor. This waste will not affect the depolymerisation reaction, hence it stays intact and needs to be separated physically at the end of the process. In order to retain both monomers in the solution, liquefiers can be added to keep the produced TPA liquid at this stage.

- **Neutralisation:** If acidic or basic hydrolysis is used, the reaction mixture needs to be neutralised (at room temperature).
- **Crystallisation:** Crystal growth steps to recover TPA. It can then be filtered off, washed with water and dried in an oven (up to about 120 °C).
- **Distillation:** To purify ethylene glycol, up to about 250 °C.

Enzymatic depolymerisation

Enzymatic depolymerisation selectively breaks down PET into monomers such as terephthalic acid (TPA) and ethylene glycol (EG). The purification process involves:

- **Filtration:** Separates solid residues and undigested materials.
- **Precipitation:** TPA is precipitated (and crystallised) under controlled pH conditions and washed to remove contaminants.
- **Solvent Extraction:** Uses solvents or ion exchange to remove organic impurities from ethylene glycol.
- **Distillation:** Ethylene glycol is purified through vacuum distillation to remove residual contaminants.
- **Enzyme Recovery:** Microfiltration or nanofiltration can be used to recover and reuse enzymes where applicable.
- **Drying:** Purified TPA is dried for reuse in polymerisation.

Conclusion

This chapter has explored the landscape of chemical recycling technologies. Chemical recycling offers the ability to break down plastic waste into monomers or shorter hydrocarbon chains, enabling the recovery of materials from contaminated, mixed, or degraded plastic streams that would otherwise be landfilled or incinerated.

Two major branches of processes have been examined: thermal decomposition (e.g., pyrolysis, gasification, and hydrothermal liquefaction) and chemical depolymerisation (notably glycolysis, methanolysis, and hydrolysis of polyesters). These processes differ significantly in feedstock requirements, product outputs, and technology maturity, but all aim to recover hydrocarbons or monomers suitable for integration into petrochemical production chains.

Modular process descriptions were provided, covering feedstock preparation, reaction conditions, and subsequent purification steps. Key challenges identified include the need for high energy input, complex upgrading steps to remove heteroatoms and impurities, and the variability of feedstock composition. Purification, especially hydrotreatment, is essential for producing naphtha-like products that meet steam cracker specifications. Quality control and process integration remain critical for ensuring reliable, high-purity outputs.

Despite its high potential, chemical recycling is still in a scale-up phase, with most installations in Europe are either at demonstration scale or limited to narrow plastic streams. The economic and environmental viability of these processes depends heavily on feedstock consistency, energy efficiency, and the development of robust purification methods.

In summary, chemical recycling has emerged as a recycling technology suitable for converting low-value, complex plastic waste into virgin-quality materials. However, widespread deployment will require further innovation, process improvement, infrastructure investment, and regulatory clarity to reach its full potential in a circular plastics economy.

FINAL CONCLUSIONS

The transition to a circular plastics economy is gaining momentum across Europe, driven by ambitious policy frameworks such as the Circular Economy Action Plan (CEAP) and the Packaging and Packaging Waste Regulation (PPWR). These initiatives, alongside emerging recycled content targets for sectors like Waste Electrical and Electronic Equipment (WEEE) and End-of-Life Vehicles (ELV), are accelerating the demand for scalable, high-performance recycling systems. Achieving these targets, however, will require coordinated investments in infrastructure, advanced technologies, and workforce development.

This report has mapped the current landscape of plastic recycling technologies, with a primary focus on sorting processes and recycling methods across key waste streams, namely plastic packaging, WEEE, ELV, and construction plastics such as PVC. Each of these streams presents distinct challenges, from complex contamination in packaging to the depollution and dismantling requirements of WEEE and ELV. Rigid frameworks for collection, sorting, and pre-treatment are essential to enable effective recycling, especially in recycling processes where material quality and consistency are critical.

Sorting technologies, such as near-infrared (NIR) detection, sink-float separation, ballistic sorting, and windsifting, remain central to separating plastics by polymer type and physical properties. Increasingly, artificial intelligence (AI) and robotics are being integrated into sorting systems to improve precision and throughput.

In the mechanical recycling process, standardised process modules, such as grinding, washing, drying, and extrusion, are applied across streams but adapted to the material-specific requirements of each. Nonetheless, the mechanical recycling industry continues to face technical challenges, including contamination from inks, adhesives, and additives; difficulties in identifying black or multi-layer plastics; and the incompatibility of certain materials with established processes. These challenges highlight the need for upstream design-for-recycling (DfR) practices and harmonised packaging standards. Enhanced collaboration between producers, recyclers, and policymakers is essential to improve recyclability and reduce material losses across the system.

Dissolution recycling offers a promising approach for handling hard-to-recycle plastic waste streams by enabling the targeted purification of specific polymers. This process leverages selective solvent interactions to separate polymers from additives and other contaminants. While still emerging as an industrial practice, dissolution recycling holds potential for producing high-purity recyclates suitable for sensitive applications. However, its deployment is currently limited to pilot and early commercial plants, with challenges related to solvent use, safety, and regulatory compliance needing to be addressed.

Chemical recycling encompasses methods such as thermal decomposition and chemical depolymerisation, which break down polymers into their monomers or other valuable chemicals.

Chemical recycling is still in its early stages, with limited deployment in pilot and commercial plants. The technology shows promise for improving the purity and performance of recycled plastics, but it faces challenges related to process complexity, safety, environmental impact, and regulatory compliance.

Ultimately, the efficiency and sustainability of plastic recycling depend not only on technological innovation but also on systems-level coordination. Continued policy support, harmonised quality standards, and strategic public-private partnerships will be essential to close the loop and meet Europe’s circular economy goals.

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