PRIMUS

WP1. Common recyclates

Task 1.1

Towards an EU broadly accepted definition of Recyclate

Deliverable 1.1

Report on enhancing systemic actions to boost the circularity of target waste streams

Key highlights of the deliverable

- There are several barriers across the value chain that are due to direct or indirect causes of legislation
- Various solutions to specific barriers can be suggested to increase the overall circularity and uptake of recyclates
- However, several barriers with no foreseen solutions exist, which would require further research and development

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DISCLAIMER

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ABBREVIATIONS

ABS: Acrylonitrile Butadiene Styrene

AI: Artificial Intelligence

BBP: Butyl Benzyl Phthalate

BFR: Brominated Flame Retardant

CLP: Classification, Labelling and Packaging Regulation

CPA: Circular Plastics Alliance

DBP: Dibutyl Phthalate

deca-BDE: Decabromodiphenyl Ether

DEHP: Bis (2-ethylhexyl) Phthalate

DIBP: Diisobutyl Phthalate

EC: European Commission

ECHA: European Chemicals Agency

EEA: European Economic Area

EEE: Electrical and Electronic Equipment

ELV: End-of-Life Vehicles

EOL: End of Life

EoW: End of Waste

EPR: Extended Producer Responsibility

ESPR: European Strategy for Plastics in a Circular Economy

EU: European Union

FCM: Food Contact Materials

GHG: Greenhouse Gas Emissions

GHS: Globally Harmonized System of Classification and Labeling of Chemicals

GMP: Good Manufacturing Practices

HBCDD: Hexabromocyclododecane

HCBD: Hexachlorobutadiene

HDPE/PP: High-Density Polyethylene/Polypropylene

hepta-BDE: Heptabromodiphenyl Ether

hexa-BDE: Hexabromodiphenyl Ether

JRC: Joint Research Centre

LCA: Life Cycle Assessment

LDPE: Low-Density Polyethylene

LoW: List of waste

MON: MONDRAGON Corporation

MS: Member States

NIR: Near Infrared Sorting

PA: Polyamide

PAHs: Polycyclic Aromatic Hydrocarbons

PBDE: Polybrominated Diphenyl Ethers

PBP: Polybrominated Biphenyls

PCB: Polychlorinated Biphenyls

PCDD/Fs: Polychlorinated Dibenzo-p-dioxins and Dibenzofurans

PCDDs: Polychlorinated Dibenzo-p-dioxins

PCDFs: Polychlorinated Dibenzofurans

PCP: Pentachlorophenol

PE: Polyethylene

penta-BDE: Pentabromodiphenyl Ether

PET: Polyethylene Terephthalate

PFAS: Per- and Polyfluoroalkyl Substances

PFHxS: Perfluorohexane Sulfonic Acid

PFOA: Perfluorooctanoic Acid

PFOS: Perfluorooctane Sulfonic Acid

POP: Persistent Organic Pollutant

PP: Polypropylene

PPWD: Packaging and the Packaging Waste Directive

PRE: Plastics Recyclers Europe

PS: Polystyrene

PTFE: Polytetrafluoroethylene

PUR: Polyurethane

PVC: Polyvinyl Chloride

REACH: Registration, Evaluation, Authorisation and Restriction of Chemicals

RIA: Research and Innovation Action

RoHS: Restriction of Hazardous Substances in electrical and Electronic Equipment

SCCPs: Short-Chain Chlorinated Paraffins

SVHC: Substances of Very High Concern

tetra-BDE: Tetrabromodiphenyl Ether

UNEP: United Nations Environment Programme

VTT: Technical Research Centre of Finland Ltd.

WEEE: Waste Electronics and Electrical Equipment

WFD: Waste Framework Directive

EXECUTIVE SUMMARY

This deliverable is part of the EU-project PRIMUS and investigated how enhancing systemic actions can be used to boost circularity of the project's target waste streams. This is done by outlining the key legislation surrounding the waste to product interface of plastic waste from waste electronics and electrical equipment (WEEE) as well as end-of-life vehicles (ELV) waste streams. The legislative review is followed by identification of barriers that can be seen in current legislations. This section also includes suggestions for actions on how to boost the uptake of recyclates in added value products.

The legislative review focused first on framework legislations and initiatives like the European Plastic Strategy, Circular Plastics Alliance, and Chemical Strategy for Sustainability. This is followed by a detailed look into the key Directives scoping WEEE and ELV, such as the WEEE Directive (2012/19/EU) and the ELV Directive (2000/53/EU). Different waste legislations that are critical to the scope of the project are described in the next sections were the focus is kept on the Waste Framework Directive, POP Annex IV and the End of Waste Status. Also, the different product legislations are reviewed to provide an overall understanding of the complex legal network that guides the use and production of different products in EU. Altogether, an overview of the plastic waste-to-product interface is formed.

Several barriers across the focus value chains were identified together with proposed solutions. The key findings are that there are several barriers that are either directly or indirectly caused by legislation, which hinders transitioning to circular economy. For example, the lack of end-of-waste criteria for plastic waste management was identified as a barrier, and for example overlapping - and sometimes even contradictory - and quickly evolving legislation creates its own challenges. It was also discovered that some unresolved barriers are present at the waste to product interface. These barriers span throughout the whole lifecycle from collection to manufacturing and life services and can pose significant environmental and health risks. These unresolved barriers include, for example, substandard practices in waste management, no dedicated market for recyclates and the generation of microplastics. The work to identify and validate barriers and actions to boost uptake of recyclates was done in collaboration with value chain actors and experts from the field via interviews and a joint workshop.

PRIMUS PROJECT

PRIMUS project is dedicated to significantly contribute to the goals of the European Strategy for Plastics and enhance the amount of quality and safe recycled plastics that enter the European markets. PRIMUS is a project funded by the Horizon Europe in the following call: HORIZON-CL4-2021-RESILIENCE-01-10: Paving the way to an increased share of recycled plastics in added value products (RIA). PRIMUS is a 3-year project with a total budget of 7 M€. PRIMUS has 10 partners, and 2 affiliated entities.

PRIMUS will actively engage with the plastics value chain stakeholders and innovatively develop novel methods and technologies to significantly increase the circularity, and production and use of sustainable, safe and quality recyclates in added value products. The main technological focuses are on advanced mechanical recycling coupled with broad analytics and novel pretreatment methods for removal of hazardous substances and counteracting degradation. waste streams from waste electronics and electrical equipment (WEEE) and end-of-life vehicles (PRIMUS will produce 4 demonstrations where new added value products will be made from recycled and upgraded non- or underutilized plastic ELV). The four demo products will be automotive interior parts, automotive cooling circuits and its elements, a food contact application refrigerator, and a closed-loop demonstration of washing machine seals.

The project aims at establishing EU widely accepted and transparent procedures to control quality and safety of recyclates, especially for the waste streams containing hazardous substances like brominated flame retardants. The framework related work will include broad engagement of the European plastics sector and recyclers, but also the society, citizens and communities as well as consumers. Safety and trackability back to origin, traceability, are consistent and overlapping themes in PRIMUS. PRIMUS will not only technically and industrially support the uptake of recyclates in products but will also address and support the concerns of the society and enhance the uptake of products that have recycled content.

1 INTRODUCTION

1.1 Scope

This deliverable outlines the key legislation surrounding the waste to product interface of plastic waste from waste electronics and electrical equipment (WEEE) and end-of-life vehicles (ELV) waste streams. The review is followed by identifications of barriers in current legislation and suggestions for actions to boost the uptake of recyclates in added value products.

1.2 Audience

Value chain actors, policy makers

1.3 Contributions of partners

The following Table 1 depicts the main contributions from participant partners in the development of this deliverable.

Table 1. Partners' contributions

Participant short name	Contributions
VTT	Overall content and review, conducting interviews
PRE	WP lead, overall content and review, conducting interviews and lead in the waste to product interface workshop
MON	Conducting interviews and organisation of the waste to product interface workshop

1.4 Structure

- **Section 1:** Contains an overview of this document, providing its Scope, Audience, and Structure
- **Section 2**: Contains the objectives and expected impacts of the project and completed work
- **Section 3** : Contains the mapping of the key legislations
- **Section 4**: Contains the identified legislation related barriers
- **Section 5**: Contains suggestion for actions to boost the uptake of recyclates
- **Section 6**: Provides the conclusions

2 OBJECTIVES AND EXPECTED IMPACT

2.1 Objective

This report is aimed to review the current key legislations related to the WEEE and ELV plastic waste streams and the waste to product interface. It also entailed interviews of value chain actors as well as a Pan-European workshop to identify and validate legislative barriers and needed actions to boost the uptake of recyclates. The overall aim is to identify and enhance systemic actions to boost the circularity of target waste streams of PRIMUS.

2.2 Expected Impact

Overall, the deliverable will support development of policy recommendations to further help improve the recycling and uptake of recyclates in added value products in the European markets.

3 MAPPING OF THE KEY LEGISLATIONS SURROUNDING THE WASTE TO PRODUCT INTERFACE

This chapter entails concise overviews of the framework legislations and initiatives, directives scoping WEEE and ELV, waste legislation and product legislation.

3.1 Framework legislations and initiatives

3.1.1 European Plastics Strategy

The European Plastics Strategy (Council of the EU , 2018) is part of the EU's circular economy action plan. It can be considered as a key element in the transition towards carbon neutral and circular economy in Europe by contributing to the 2030 Sustainable Development Goals, the Paris Climate Agreement objectives and the EU's industrial policy objectives.

Key objectives (Council of the EU , 2018) of the European Plastics Strategy are to protect our environment, to reduce marine litter, greenhouse gas emissions (GHG) and our dependence on imported fossil fuels. In addition to these, it will also support more sustainable and safer consumption activities and production patterns for plastics across Europe. The aim is to change the way plastic products are designed, produced, used and recycled in the EU to cater for greener transition across the whole plastics value chain.

To achieve the above objectives, the strategy states several EU-wide and national measures with detailed actions that support the execution of the strategy. The key measures (Commission of EU, 2018) on EU level are:

- Improving the economics and quality of plastics recycling
- Curbing plastic waste and littering
- Driving investment and innovation towards circular solutions
- Harnessing global action

Each key measure includes several targeted actions that aim to improve product design, to boost recycled content, to improve separate collection of plastic waste, to reduce single-use plastics, curb microplastics pollution and to tackle sea-based sources of marine litter, among others. The full list of actions and their timelines can be found from the Annex 1 (Commission of EU, 2018) of the strategy. The strategy also includes several voluntary pledges aimed for actors across the plastics value chain, such as the Circular Plastics Alliance (Commission of EU, n.d.). National level measures listed in the strategy are directed to the authorities and industry and are meant to encourage the transition to circular plastics on national level. These include, for example, the promotion existing alternatives to single-use plastic items, favouring reusable and recycled plastics in public procurement and considering the introduction of Extended Producer Responsibility (EPR) scheme. Most of the actions mentioned in the European Plastics Strategy have been started at 2018 and have already been finished but some are still ongoing.

3.1.2 Circular Plastics Alliance

Circular Plastics Alliance (CPA) (Commission of EU, n.d.) is an initiative under the European Plastics strategy that gathers a network of actors that together aim to boost the EU market for recycled plastics. It is open for all European actors across the plastics value chain to join and currently includes over 330 organisations representing industry, academia and public authorities. Its main aim is to "take action to boost the EU market for recycled plastics up to 10 million tonnes by 2025" (Commission of EU, n.d.), which is a target set in the European Plastics Strategy.

The CPA is expected to enhance the matching of supply and demand in regards of recycled plastics, which has been identified as one of the main obstacles in a well-functioning EU market for recycled plastics (Commission of EU, 2018). It aims to three main operational objectives, which are fostering short-term actions, reporting on obstacles and monitoring progress. Since its launch in 2018, it has produced several deliverables and documents that provide information on plastics recycling value chain and improve the economics and quality of plastics recycling in Europe. One of these is, for example a report from the construction working group, which provides an extensive view on the state of play for collected and sorted plastic waste from construction sector (Gardner, 2020).

3.1.3 Chemical Strategy for Sustainability

The Chemical Strategy for Sustainability (Commission of EU, 2020) was adopted in 2020 as a part of the European Union's zero pollution ambition. It is a key commitment of the European Green Deal aiming to transform Europe into sustainable and carbon neutral economy. The two main objectives of the Chemical Strategy for Sustainability are 1) to better protect the citizens and the environment and 2) to boost innovation for safe and sustainable chemicals (Commission of EU, 2020). To achieve these objectives and to monitor progress, the Commission has established a round-table that consists of 32 members from the Member States, industry, NGOs, international organizations and scientists.

The Chemical Strategy for Sustainability states also several actions to support achievement of it's objectives. Key actions (Commission of EU, 2020) of the strategy are:

- ban the most harmful chemicals in consumer products - allow their use only where essential.
- account for the cocktail effect of chemicals when assessing risks from chemicals.
- phase out the use of per- and polyfluoroalkyl substances (PFAS) in the EU, unless their use is essential.
- boost the investment and innovation for production and use of chemicals that are safe and sustainable by design.
- promote the EU's resilience of supply and sustainability of critical chemicals.
- establish a simpler "one substance one assessment" process for the risk and hazard assessment of chemicals.

- play a leading role globally by championing and promoting high standards and not exporting chemicals banned in the EU.

Full list of the actions and their timeline can be found from the Annex (Commission of EU, 2020) of the Strategy. Together these actions and objectives contribute to minimising and substituting substances of concern. This is also relevant from the plastics recycling perspective as it has implications on the quality and consistency of recycled materials. Overall, the Strategy aims at removing substances from circulation that prevent clean recycling.

3.2 Directives scoping WEEE and ELV

3.2.1 WEEE Directive (2012/19/EU)

The objective of the waste electrical and electronic equipment (WEEE) Directive 2012/19/EU is to promote the sustainable production and consumption of WEEE. This is done by decreasing the amount of WEEE that needs to be disposed of as priority and enhancing the environmental practices of the businesses engaged in WEEE treatment. To reach these goals, WEEE Directive mandates the separate collection and proper treatment of WEEE, establishing specific targets for their collection, recovery, and recycling. It also strengthens European countries' capacity to combat illegal waste exports, making it more difficult for exporters to disguise illicit shipments of WEEE. Moreover, the Directive reduces administrative complexities by advocating for the harmonization of national electrical and electronic equipment (EEE) registers and standardizing reporting formats. It is a revised version of first WEEE Directive 2002/96/EC to tackle the rapidly increasing waste stream. (European Commission, n.d.)

In 2018, Europe (EU-28) accumulated a total of 4.4 million tons of WEEE. Depending on the type of appliance, 10 to 50 percent of this waste was comprised of plastic materials, primarily thermoplastics. (Cafiero, et al., 2021) Managing plastic within WEEE presents a significant challenge due to its complex polymer structure and the inclusion of various additives. Plastic recycling is also weighed against the potential risks considering their hazardous substances, mainly legacy brominated fire retardants and heavy metals (Buekens & Yang, 2014). In addition to that, recycled plastics face limitations of market. WEEE plastics, therefore, often undergo downcycling, incineration, or end up in landfills. As the use of plastics in EEE continues to rise, the management of WEEE plastics raises legal concerns at the intersection of chemical, product, and waste regulations. (WEEE Forum, 2017) Regarding the circularity of WEEE plastics towards product integration, the WEEE Directive concerns:

Product design

Article 4 stipulated that Member States shall promote collaboration between manufacturers and recyclers and implement measures to encourage the design and manufacturing of EEE aiming at facilitating the reuse, dismantling, and recovery of WEEE) along with its components and materials. Within this context, Member States are required to take suitable actions to ensure that the ecodesign standards that promote the reuse and treatment of WEEE, as established in Directive 2009/125/EC,

are applied to by producers. Producers should not obstruct the reuse of WEEE through specific design characteristics or manufacturing methods, unless these features or processes offer clear and compelling advantages, such as enhanced environmental protection and safety requirements. (EUR-Lex, 2018)

Separate collection

Article 5 stated that Member States shall implement effective measures aimed at reducing the inclusion of WEEE in unsorted municipal waste, proper handling of all gathered WEEE and attaining a substantial level of separate collection of WEEE. Additionally, Member States shall establish systems that allow end-users and distributors to return such waste without incurring any cost. They are also responsible for making sure that the requisite collection facilities are readily available and easily accessible, considering factors like population density. (EUR-Lex, 2018)

Disposal and transport of collected WEEE

Article 6 outlined that Member States shall forbid the disposal of separately gathered WEEE that has not yet undergone the designated treatment outlined in Article 8. Furthermore, Member States shall guarantee that the collection and transportation of separately collected WEEE is executed in a manner that provides the best conditions for preparing it for reusing, recycling, and confinement of hazardous substances. (EUR-Lex, 2018)

Extended producer responsibility

Article 7 emphasized that the principle of ''extended producer responsibility'' should be promoted by Member States. As stipulated in Articles 12 and 13, Member States shall ensure that producers take on the responsibility, including financial support, for the collection, treatment, recovery, and environmentally responsible disposal of WEEE from both private households (Article 12) and users other than private households as a result of products placed on the market (Article 13). Article 8 further specified that producers or their authorized representatives must establish systems for the recovery of WEEE using the most advanced techniques available. These systems may be established either individually by producers or collectively. (zu Castell-Rüdenhausen, et al., 2021; EUR-Lex, 2018)

Proper treatment

Article 8 stated that Member States shall guarantee appropriate handling for all separately collected WEEE. This proper treatment, apart from preparing for re-use, and recovery or recycling operations, must at least involve the removal of all fluids and a selective treatment, such as plastic containing brominated flame retardants, in accordance with Annex VII. (EUR-Lex, 2018)

According to article 10, the treatment process can also occur beyond the Member State or the Union's borders, as long as the transport of WEEE follows to the EU Regulation governing the export of specific waste for recovery. If WEEE is sent out of the Union, it will only be considered towards meeting the obligations and goals outlined in Article 11 of this Directive if, in accordance with EU regulation, the exporter

can demonstrate that the treatment occurred under conditions equivalent to those required by this Directive. (EUR-Lex, 2018)

Collection and recovery target

Article 7 specified that from 2018, the yearly minimum collection target should be either 65% of the average weight of EEE placed on the market in the three preceding years in the relevant Member State, or alternatively, 85% of the WEEE generated within that Member State's territory (EUR-Lex, 2018)

Article 11 stated that for all separately collected WEEE in accordance with Article 5, and subsequently treated according to Articles 8, 9, and 10, Member States are responsible for ensuring that producers meet the minimum recovery targets as outlined in Annex V. These targets encompass a range of 50% to 80% for recovery and 20% to 75% for recycling. (EUR-Lex, 2018)

Reporting and information

According to Article 16, Member States shall establish a register of producers, which encompasses those supplying EEE through distance communication methods (EUR-Lex, 2018). Upon registering each producer provides the details outlined in Annex X, Part A, which includes (zu Castell-Rüdenhausen, et al., 2021):

- the quantity of EEE placed on the national market.
- the quantity, by weight, of WEEE separately collected, recycled (including prepared for reuse), recovered and disposed of within the Member State or shipped within or outside the EU.

This registry shall serve to monitor compliance with the Directive's stipulations. Moreover, to ensure uniform conditions for the reporting, the Commission has adopted Implementing Regulation 2019/290/EU, establishing the format for registration and reporting and the frequency of reporting to the register. (zu Castell-Rüdenhausen, et al., 2021)

3.2.2 ELV Directive (2000/53/EU)

The ELV Directive (2000/53/EU) establishes clear targets for end-of-life vehicles (ELVs) and their components, while also prohibiting the use of hazardous substances (lead, mercury, cadmium, and hexavalent chromium) in new vehicle manufacturing, except in specific exemptions where suitable alternatives are unavailable. In addition, the Directive establishes clear goals for the reuse, recycling, and recovery of ELVs, with the following aims (European Commission, n.d.):

- minimize and control waste from end-of-life vehicles and their components.
- enhance the environmental performance of all stakeholders involved in the vehicle life cycle.

This Directive applies to passenger vehicles and small trucks but excluding big trucks, vintage vehicles, special-use vehicles, and motorcycles. Since the introduction of this Directive, many revisions have been implemented. Additionally, the EU has

introduced various associated regulations, including the Directive concerning the approval of motor vehicles with regards to their potential for reuse, recyclability, and recoverability. In 2021, an evaluation of the ELV Directive was initiated, leading to the development of a proposed new regulation in 2023. (European Commission, n.d.)

In 2019, the automotive sector accounted for approximately 10% of plastic demand, making it the third-largest sector, consuming 5.1 million tonnes annually. Plastics such as PP, PUR, PA, PE, ABS, and PET, constitute between 12% to 16% of the total weight of vehicles. In 2017, there were 11 million vehicles that reached the end of life. Those decommissioned ELVs yielded approximately 1 million tonnes of plastic waste required proper treatment. Despite advancements in circular practices within the automotive industry, treating plastics from End-of-Life Vehicles (ELVs) remains a challenge. A significant portion of ELV recyclers in the EU do not fully engage in recycling plastic materials, resulting in a majority of ELV plastics being either landfilled or used for energy recovery. To solve the pressing sustainable challenges of growing automotive sector and resource scarcity, policymakers are exploring measures promoting the use of recycled content, aiming to boost the circularity of materials. (Maury, et al., 2023) Regarding the circularity of ELV plastics towards product integration, the ELV Directive concerns:

Design and manufacturing

Article 7 mandates vehicle and equipment manufacturers to prioritize dismantling, reuse, and recovery in their product design and production processes, ensuring that new vehicles meet the following criteria (EUR-Lex, 2023):

- reusable and/or recyclable to a minimum of 85% by weight per vehicle
- reusable and/or recoverable to a minimum of 95% by weight per vehicle.

Article 8 further requires producers and manufacturers to implement component and material coding standards for streamlined identification of reusable and recoverable elements. Component manufacturers must provide authorized treatment facilities with the necessary details on how to dismantle, store, and test the components. Additionally, vehicle producers must provide dismantling information for new vehicles introduced to the market. This information should cover various vehicle components and materials, as well as the specific locations of any hazardous substances within the vehicles. (zu Castell-Rüdenhausen, et al., 2021)

Collection

Article 5 outlined the obligations of manufacturers, importers, and distributors to establish collection systems for End-of-Life Vehicles (ELVs) as well as, when technically possible, for used parts from repaired passenger cars. Manufacturers are responsible for covering the full or a substantial portion of the costs associated with transporting an ELV to a waste treatment facility. Vehicle owners, in turn, should not bear any expenses when delivering an ELV to an authorized waste treatment facility, except in exceptional cases such as when the engine is absent or the ELV contains waste. In addition, Member States are mandated to establish a system wherein the submission of a certificate of destruction is a prerequisite for the deregistration of an end-of-life

vehicle. This certificate shall be issued to the vehicle owner when the end-of life vehicle is delivered to a treatment facility. (EUR-Lex, 2023)

Treatment

Article 6 outlined that Member States must take the necessary steps to ensure that all end-of-life vehicles are stored (even temporarily) and treated following the minimum technical standards detailed in Annex I of this Directive. Furthermore, Member States are required to ensure that any facility or business engaged in treatment operations meets the following obligations as specified in Annex I (EUR-Lex, 2023):

- end-of life vehicles shall be stripped before further treatment or other equivalent arrangements are made in order to reduce any adverse impact on the environment.
- hazardous materials and components shall be removed and segregated in a selective way so as not to contaminate subsequent shredder waste from end-of life vehicles.
- stripping operations and storage shall be carried out in such a way as to ensure the suitability of vehicle components for reuse and recovery, and in particular for recycling.

Regarding ELV plastics, Annex I (4. Treatment operations in order to promote recycling) requires the removal of tyres and large plastic components (bumpers, dashboard, fluid containers, etc), if these materials are not separated in the shredding process to enable effective recycling. (EUR-Lex, 2023)

Reporting and information

Article 9 stated that Member States shall submit reports to the Commission every three years, detailing the implementation of this Directive concerning the reuse, recycling, and recovery of ELVs and their components (EUR-Lex, 2023). Additionally, Member States must compel relevant economic operators to disclose information regarding (EUR-Lex, 2023):

- the design of vehicles and their components with a view to their recoverability and recyclability,
- the environmentally sound treatment of end-of life vehicles, in particular the removal of all fluids and dismantling,
- the development and optimisation of ways to reuse, recycle and recover end-of life vehicles and their components,
- the progress achieved with regard to recovery and recycling to reduce the waste to be disposed of and to increase the recovery and recycling rates.

Producers are obligated to provide this information to potential vehicle purchasers, incorporating it into promotional materials used for new vehicle marketing.

Proposed new ELV regulation

On July 13, 2023, the Commission proposed a new Regulation concerning end-of-life vehicles after conducting a review. Aligned with the goals of the European Green Deal and the Circular Economy Action Plan, this proposal for an ELV Regulation is an

advancement building on two existing Directives: Directive 2000/53/EC addressing end-of-life vehicles and Directive 2005/64/EC concerning the type-approval of motor vehicles in terms of their reusability, recyclability, and recoverability. The suggested new guidelines encompass all facets of a vehicle's lifecycle, spanning from its initial design and introduction to the market to its ultimate treatment at the end-of-life stage (European Commision, n.d.):

- Design circular
  - improve circular design of vehicles to facilitate removal of materials, parts and components for reuse and recycling
  - set minimum reusability, recyclability, and recoverability standards
  - mandate vehicles to be equipped with a circularity passport documenting their lifecycle and environmental impact.
- Use recycled content
  - ensure that at least 25% of plastic used to build a vehicle comes from recycling (of which 25% from recycled ELVs)
  - declaring recycled content levels
- Collect more and smarter
  - prevent missing ELVs through more inspections and interoperability of national vehicle registration systems
  - improve distinction between used vehicles and end-of-life vehicles
  - ban on exporting vehicles that aren't roadworthy
- Treat better
  - impose restrictions on landfill usage
  - mandating the extraction of valuable components
  - require a 30% plastics recycling rate
  - prevent the mixing of end-of-life vehicle waste with other types
  - providing incentives for spare parts sales can lead to the retrieval of higher-quality raw materials.
- Make producers responsible
  - ensure that producers are made financially responsible for vehicles when they become waste, to ensure proper financing for mandatory ELV treatment operations and incentivise recyclers to improve quality
  - improve cooperation between manufacturers and recyclers

3.3 **Waste legislation**

3.3.1 Waste Framework Directive (2008/98/EC)

The Waste Framework Directive (WFD, 2008/98/EC) sets the basic concepts and definitions related to waste management, such as definitions of waste, recycling, recovery, end-of-waste criteria, and how to distinguish between waste and by-products. The Directive lays down measures to protect the environment and human health via two key objectives: to prevent and reduce the negative impacts caused by the generation and management of waste and to improve resource efficiency through reuse, recycling and recovery. The Directive also defines the key principles of waste management, i.e. the precautionary principle, the proximity principle, the self-sufficiency principle and the waste hierarchy (illustrated in Figure 1). The EU waste

management policies are highly built upon the waste hierarchy, establishing the order of preference for managing and disposing of waste. The Directive also introduces the polluter pays principle and the extended producer responsibility. (European Commission, 2018)

Figure 1. Waste hierarchy according to the European Commission and the WFD (European Commission, n.d.)

Hazardous wastes pose a greater risk to the environment and human health than non-hazardous waste and therefore require a stricter control regime. The WFD provides additional monitoring and control obligations for hazardous waste, and also bans the mixing of hazardous waste with other waste. The European List of Waste (LoW) provides more information on the classification of all types of waste (including hazardous). The LoW provides an EU-wide common terminology for waste classification, including references to other directives for limit values of concentration of hazardous substances, such as the RoHS directive (2011/65/EU) for limit values of certain hazardous substances in electrical and electronic equipment (EEE), the POP Regulation (2019/1021/EU) limiting the use of Persistent organic pollutants (POPs) and the REACH Regulation (1907/2006/EC) restricting the use of specific chemicals. The classification of waste is based on the LoW and Annex III to the WFD. (European Commission, 2018; European Commission, 2000)

3.3.2 POP Annex IV (Regulation (EU) 2019/1021)

Persistent organic pollutants (POPs) consisting of organic chemicals have resistance to degradation via chemical, biological, or photolytic means. As majority of these pollutants contain harmful and toxic chemical compounds, they hold a possibility of accumulation in the living organisms through different media (ECHA, n.d.). For instance, researchers have found traces of POPs entering in human bodies primarily from the food chain. Higher concentrations and continuous exposure of these harmful substances to human beings can lead to various neurological, cardiovascular,

respiratory, immunological, reproductive, mutagenic, and carcinogenic effects (Sophie & Nicolas, 2022). Air, water, and migratory species can serve as active carriers for these POPs across different countries and regions around the world, thus adversely affecting the health of various terrestrial and aquatic as well as the surrounding environment. The Arctic, the Alps and the Baltic Sea are some examples of regions in EU with higher POP concentrations and are referred to as "POP sinks" (Alharbi;Khattab;& Ali, 2018).

To mitigate these POPs, a regulation (2019/1021) was implemented in 1970s by the United Nations Environment Programme (UNEP). Further, in 1995, the UNEP issued a call for international measures to address POPs. In 2001, a global environmental agreement called as the Stockholm Convention was signed for POPs and became effective in 2004 (Lallas, 2017). Its primary objective is to eliminate or place restrictions on the production and utilization of POPs. The adoption of the Stockholm Convention into EU law was accomplished through Regulation (EC) No 850/2004. Subsequently, in 2019, this regulation was replaced by Regulation (EU) 2019/1021 under the European Green Deal programme. The regulation follows the guidelines described in Stockholm Convention and Aarhus Protocol, where POPs are categorized based on 1) elimination of production and use, 2) restricted in production and use, 3) unintentionally produced, and 4) chemicals that are under investigation. (European Parliament, EPRS, 2021)

These regulations and guidelines will assist the European Chemical Agency (ECHA) to identify, track, inform, and act on the current as well as the incoming POPs in accordance with the POPs Union Implementation Plan. However, the biggest challenge in mitigating POPs has been their continuous presence in the multiple waste streams involving construction materials, textiles, WEEEs, and ELVs. This is due to barring of disposal and recovery practices that could potentially lead to the retrieval, recycling, reclamation, or reuse of POPs. Furthermore, the Waste Framework Directive (2008/98/EC) and the Technical Guidelines of the Basel Convention explicitly prohibit the dilution of waste. Thus, creating further hinderances in achieving a successful transition from a linear to circular economy. (European Parliament, EPRS, 2021)

To address these challenges, the POP regulatory framework amending Annex IV and V was revised by the EU commission. The aim of the framework was to determine the efficient waste disposal (Annex IV) and recovery (Annex V) strategies for the materials containing these harmful POPs (exceeding the concentration limits of substances) i.e., whether the waste can be recycled, irreversibly transformed, or destroyed completely. The framework also emphasized on the strategy development and execution for minimizing the entry of these POPs in the ecosystem. As per the Annex IV of EU 2019/1021, the concentration limits for certain groups of POPs available in the database were updated, and the concentration limits for new POPs were also described in the framework. (European Parliament, EPRS, 2021; European Commission, Directorate-General for Environment, 2021)

Error! Not a valid bookmark self-reference. represents some of the newly recorded POPs mentioned in Annex IV such as pentachlorophenol, its salts and esters (found in chemically treated wood and textiles), perfluorooctanoic acid (PFOA), its salts and derivatives (found in waterproof textiles and fire-fighting foams), and dicofol

(pesticide previously used in agriculture). The framework also updated the existing concentration limits for previously encountered POPs involving flame retardants such as polybrominated diphenyl ethers (PBDEs) often used in plastics and textiles, hexabromocyclododecane (HBCDD) used in polystyrene (PS) insulation panels, short-chain chlorinated paraffins (SCCPs) used in rubbers and plastics. The concentration limits for POPs containing dioxins (PCDDs) and furans (PCDFs) were also proposed as these substances are present as impurities in fly ash coming from the incinerator and industrial waste, dioxin-like PCBs, and are present in some ashes and oils. (European Commission, Directorate-General for Environment, 2021)

These concentration levels of POPs found in waste will play a crucial role in determining the suitable treatments and handling procedures, depending on whether the specific concentration thresholds are surpassed or not. The two distinct concentration thresholds for waste plastics would also assist in selection of treatment methods. However, exceeding the higher thresholds for the new substances in Annex IV may trigger additional constraints and might require further revision of regulation. Similarly, when the concentration falls below the lower threshold limit, treatment methods may be employed that do not result in the complete destruction or irreversible transformation of POPs. (European Commission, Directorate-General for Environment, 2021)

The categorisation of POP waste according to the Waste Framework Directive (2008/98/EC) and the European List of Waste (Commission Decision 2014/955/EU) as hazardous or non-hazardous waste would assist in identification of significant implications for its treatment, necessitating specific environmental permits for handling, packaging, and marketing, as well as record-keeping requirements. (European Parliament, EPRS, 2021)

Table 2. Summary of the chemical substances recasted in Annex IV of the POPs regulation (European Parliament, EPRS, 2021)

Group of substances	Purpose	End applications	Status
Polybrominated diphenyl ethers (PBDEs): Tetra-, Penta-, Hexa-, Hepta- and Deca-bromodiphenyl ether	• Flame retardants. • Used in conjunction with antimony trioxide to provide fire-resistance to plastics, textiles and other materials.	• Certain plastics and textiles contained in electrical and electronic equipment (EEE) and in vehicles. • Plastics used in construction, and in textiles used in upholstered furniture, tarpaulins, etc.	Existing values updated
Hexabromocyclod odecane (HBCDD)	• Flame retardant. • Used to provide fire resistance in expanded and extruded polystyrene insulation panels. • Limited use in other plastics (high-impact polystyrene) and textiles.	• Major use in thermal insulation panels used in construction. • Found in some EEE and in back-coated textiles.	Existing values updated
Polychlorinated dibenzo-p--dioxins and dibenzofurans (PCDD/Fs)	• No specific purpose and are not produced or added to materials intentionally. • By-products produced unintentionally in the combustion processes.	• Present as impurities in ashes from municipal waste incinerators and in other ashes. • Also, in other industrial waste.	Existing values updated
Dioxin-like PCBs	• Similar to dioxins, produced unintentionally during the combustion processes. • Present in some PCB oils historically used as dielectric fluid or plasticiser.	• Present as an impurity in some ashes. • Potentially present in oils from some remaining electrical transformers and capacitors.	Existing values updated
Short-chain chlorinated paraffins (SCCPs)	• Flame retardant. • Used in some rubber and plastic materials.	• Used in rubbers for industrial and mining conveyor belts, hoses, cables, and seals.	Existing values updated

		• Soft Polyvinyl Chloride (PVC) plastic articles. In some construction sealants and paints.	
Perfluorooctanoic acid (PFOA) its salts and PFOA-related compounds	• Used to make fluorinated polymers such as PTFE (or Teflon®). • Provides water and oil repellency (water-proofing and anti-stain protection). • Protective and lubricating functions, modifier of surface tension.	• Present in some fire-fighting foams, in water-proof textiles (e.g. outdoor jackets), upholstered furniture and carpets. • In electronics such as semiconductors, coatings, seals, printed circuit boards.	Newly added
Perfluorohexane sulfonic acid (PFHxS), its salts and PFHxS related compounds	• Similar to PFOA, except not used in the manufacture of fluorine-based polymers.	• Similar to PFOA.	Newly added
Pentachlorophenol (PCP), its salts and esters	• Pesticide and biocide. • Used as a treatment to prevent wood and textiles from rotting, especially outdoors. • Production and import in the EU ceased in 2002.	• Wood used in outdoor construction such as poles, fences and awnings. • Textiles used in tents, tarpaulins.	Newly added
Dicofol	• Pesticide. • Used in agriculture, mostly in Spain until 2010.	• No evidence of stockpiles. • Probably none or very limited presence in the EU.	Newly added

3.3.3 Calculation method - Implementing Decision (EU) 2019/1004 and 2019/665

The Waste Framework Directive (WFD) and Packaging and the Packaging Waste Directive (PPWD) both contain plastics (packaging) waste recycling targets for the Members States (MS) to meet. These targets resulted in a greater effort by MS to improve the collection of plastics waste and other (packaging) waste in general.

In the past, different reporting methods by the MS led to discrepancies in the reporting of data for statistical purposes Therefore, in an amendment to the WFD and PPWD, it was agreed that the European Commission (EC) would be empowered to adopt secondary legislation to establish rules for the calculation of the attainment of targets.

Between March and June 2019, the two implementing acts were published on the Official Journal. For the PPWD, the calculation methods are included in EU 2019/665 in EU 2019/1004 for the WFD.

The current regulatory framework leaves open who is to report within MS to the authorities. Regardless of who reports, the point where reporting is done to the MS is called the "measurement point", which is defined in article 1(f) of both 2019/665 and 2019/1004:

*'**measurement point**' means the point where the mass of waste materials is measured with a view to determining the amount of waste at the calculation point;*

The Regulation defines clearly where the calculation point is to be placed, i.e. where one has to count material as recycled. The calculation point for plastics is defined in article 1(e) as:

*'**calculation point**' means the point where* [municipal/packaging][1] *waste materials enter the recycling operation whereby waste is reprocessed into products, materials or substances that are not waste or the point where waste materials cease to be waste as a result of a preparatory operation before being reprocessed;*

Annex I of the Implementing Decision (EU) 2019/1004, mirrored by (EU) 2019/665 Annex II, provides further clarification on the calculation point for plastics to be set at:

Material	Calculation Point
Plastics	*Plastic separated by polymers that does not undergo further processing before entering pelletisation, extrusion, or moulding operations.* *Plastic flakes that do not undergo further processing before their use in a final product.*

The calculation point is located firmly in the recycler's facility. Therefore, it is clear that regardless of which entity has to report to the MS (the sorting centre or the recycler directly), the calculation should be performed by the recycler itself. In the event that the measurement point is assigned by a MS to a sorting centre, the recycler should provide information to the sorting centre enabling them to report towards the MS.

[1] EU 2019/1004 speaks of municipal waste, while EU 2019/665 speaks of packaging waste.

The first and most important discrepancy between legislative language and the language of the recycling industry concerns the concept of "recycling". A recycler would normally consider all operations in its plant as being recycling activities, including NIR sorting, density separation, washing, shredding, grinding, melt-filtration, etc. The legal text of the WFD (art. 3.17) however defines recycling as:

*'**recycling**' means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations;*

From this legalistic perspective, recycling is not a several step process but rather a point at which waste ceases to be waste. All activities prior to this point are from this perspective not "recycling" but "preliminary treatment" operations as defined in the implementing decisions:

*'**preliminary treatment**' means any treatment operation that* [municipal/packaging][2] *waste materials undergo before submission to the recycling operation whereby these materials are reprocessed into products, materials or substances that are not waste. This includes checking, sorting and other preparatory operations to remove non-targeted materials and to ensure high-quality recycling;*

The definition of preliminary treatment contains the term "non-targeted materials" (which implies the existence of "targeted material"), which is a term that may be differently understood by operators in the recycling industry from what the legislator understands. Within the recycling industry, targeted material is generally understood as the material in a bale of waste for which the recycler purchases the waste. For example, a PET recycler could regard the PET in a bale of PET bottles as its targeted material, while viewing the LDPE from sleeves and HDPE/PP from caps and other material impurities as non-targeted material. However, the legislation defines these terms in the implementing decisions as:

***'targeted materials'** means* [municipal/packaging][3] *waste materials that are reprocessed in a given recycling operation into products, materials or substances that are not waste;*

And

EU 2019/1004	***'non-targeted materials' means waste materials that are not reprocessed in a given recycling operation into products, materials or substances that are not waste;***
EU 2019/665	*"non-targeted materials" means, for the purposes of the calculation of the recycling targets set in points (f) to (i) of Article 6(1) of Directive 94/62/EC, waste materials that are not*

[2] EU 2019/1004 speaks of municipal waste, while EU 2019/665 speaks of packaging waste.
[3] EU 2019/1004 speaks of municipal waste, while EU 2019/665 speaks of packaging waste.

	reprocessed in a given recycling operation into products, materials or substances that are not waste;

From the legislative perspective, "targeted material" is thus not only what a recycler would like to have or what it identifies with, it is simply the material that the recycler recovers as products. To return to the example of the PET recycler, if next to the PET product it places on the market; it also places a bottle cap regrind and LDPE agglomerate on the market which it considers a product; its "targeted material" within the legal sense are the PET, HDPE/PP, and LDPE.

From this same legislative perspective, the "non-targeted materials" is not what the recycler would not like to have or what it does not see as its primary business, but rather simply the material that is not made into a product by the recycler. Again, the PET recycler would have waste in the form of dust, food residues, paper, aluminium, which leave the facility as waste.

The calculation point, as defined in the implementing decision, does provide a greater legal certainty as to when and where plastics waste can be seen as making the transition from waste to product. It does however not substitute the end-of-waste criteria. The specific calculation point for plastics is stated to be:

Material	***Calculation Point***
Plastics	*Plastic separated by polymers that does not undergo further processing before entering pelletisation, extrusion, or moulding operations.* *Plastic flakes that do not undergo further processing before their use in a final product.*

The legal text thus indicates that material that enters a pelletisation, extrusion, or moulding operation **OR** flakes that do not require further processing before use in the final product should be used as a basis for calculating the amount of recycled material. It is important that it is understood that both sentences are options and not cumulative requirements.

Please note that the first sentence point is "plastics separated by polymers". While full separation of some polymers is feasible (e.g. separation of PET from PE/PP from bottle deposit collection), the separation of other polymers may be impossible, difficult, or simply unnecessary[4]. The qualifier should be understood as separated to a degree that enables entering pelletisation, extrusion, or moulding operations without further preliminary operations.

Finally, as the calculation point is set before any form of pelletisation, extrusion, and moulding operation, it is clear that waste from melt filtration activities is still included in the amount of recycled material. See Figure *2*.

[4] A good example are wastes containing PE and PP. PE and PP can be separated from other polymers with relative ease. Further separation of PE and PP, while with great effort and additional energy consumption is possible it is rarely done because good new articles can be produced from a blend of PE and PP.

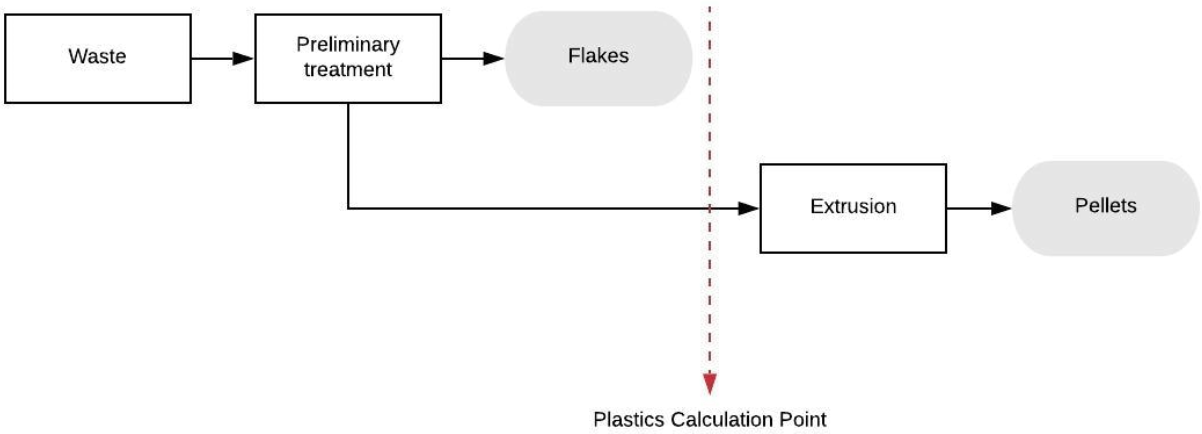

Figure 2. Schematic overview of the location of the calculation point

3.3.4 End of Waste status

End-of-waste (EoW) criteria specify when certain waste ceases to be waste and becomes a product, or a secondary raw material. The EoW criteria is specified in the WFD, that certain specified waste ceases to be waste when it has undergone a recovery operation and complies with specific criteria, such as (European Commission, 2018):

- the substance or object is commonly used for specific purposes.
- there is an existing market or demand for the substance or object.
- the use is lawful (substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products).
- the use will not lead to overall adverse environmental or human health impacts.

The WFD defines the process and general conditions for the criteria of End-of-Waste, and the implementing act 2019/1004/EC establishes detailed criteria on the conditions through a comitology procedure (i.e. Member States are consulted in the process). The Commission has set EoW criteria for some priority waste streams, i.e. iron, steel, aluminium and copper scrap, as well as glass cullet. Where an EoW has not been set at Union level, Member States can establish detailed national criteria or decide on a case-by-case basis that certain waste has ceased to be waste. However, the requirements set in the WFD must be followed, as also limit values for pollutants.

The most important conditions for the EoW for recovered plastics would relate to the use of the secondary material as an adequate alternative to primary raw materials to be used as direct input to the manufacture of plastic products. The aim with the EoW for plastics is a certificate for product quality. It would thus provide a clear differentiation between the quality-assured product and the non-quality-assured waste plastic. (zu Castell-Rüdenhausen, ym., 2021)

The Circular Economy Action plan sets a target of creating a well-functioning EU market for secondary raw materials, contributing to preventing a mismatch between

supply and demand of secondary raw materials and ensure the smooth expansion of the recycling sector in the EU. Actions to support this includes e.g. developing EU-wide end-of-waste criteria for certain waste streams. (European Commission, 2020) In 2022 the European Commission announced the start to develop EU-wide EoW criteria for plastic waste (European Commission, 2022). This was preceded by a scoping study (European Commission, 2022) and stakeholder consultation, prioritising waste streams for the development of EU-wide EoW criteria. Plastic waste was found to be a top candidate stream for developing EoW criteria, more specifically (European Commission, 2022):

- polyethylene terephthalate recovered/recycled from plastic waste
- low- and high-density polyethylene recovered/recycled from plastic waste
- mixed plastics waste recovered/recycled from plastic waste
- polystyrene and expanded polystyrene recovered/recycled from plastic waste
- polypropylene plastic recovered/recycled from plastic waste

The Commission and JRC initiated the work on the development of end-of-waste criteria for plastic waste with expected finalisation of the technical assessment by Q1 2024. A study by the JRC from 2014 defines a methodology explicitly defining EoW criteria for plastic waste for conversion, presenting five conditions for the EoW status: product quality, feedstock features, requirements on treatment, provision of information and quality assurance (JRC, 2014).

3.4 **Product legislation**

3.4.1 REACH (EC/1907/2006)

The Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH) regulation (EC/1907/2006), introduced on June 2007, represents a comprehensive framework for the control and management of chemicals within the EU. The aim of REACH is to achieve a robust level of safeguarding human health and the environment. It establishes a framework for gathering and assessing data concerning the properties and potential hazards of chemical substances. Additionally, it facilitates the unhindered circulation of chemicals within the internal market, while fostering competitiveness and driving innovation. (European Commission, n.d.; ECHA, n.d.; EU-OSHA, n.d.)

REACH is applicable to all industrially synthesized chemicals, ones involved in day-to-day products within EU/EEA region, and chemical manufacturers, end-users, downstream handlers of chemical waste, and importers from outside the EU/EEA region (ECHA, n.d.). In REACH, companies are required to register their substances, often necessitating collaboration with other entities registering the same substance. As of July 31, 2023, 103 536 registrations have been completed, encompassing 22 459 distinct substances. These registrations are attributed to more than 17 000 industries operating within the EU. (ECHA, n.d.)

Upon submission, the European Chemicals Agency (ECHA) is responsible for the reception and monitoring of individual registrations to ensuring the safety of chemical

substances, heavy metals, and other potentially harmful elements present in consumer products. Meanwhile, EU Member States conduct assessments on selected substances to address initial concerns regarding human health and environmental impacts. Authorities and ECHA's scientific committees collectively evaluate whether the risks associated with these substances can be effectively managed. In cases where risks become unmanageable, authorities retain the authority to prohibit the use of hazardous substances. They may also opt to impose restrictions on usage or require prior authorization. (ECHA, n.d.; EU-OSHA, n.d.)

As REACH primarily focuses on chemical substances used in products rather than specific products themselves, it is important to monitor different product streams to identify higher risks and impose restrictions or bans on usage of certain substances (EUR-Lex, n.d.). REACH can affect manufacturing of product in the following manner (EUR-Lex, n.d.):

1. **Identification and assessment of chemical substances in products:** REACH requires companies to identify and assess the risks associated with the use of chemical substances in their products. Manufacturers and importers of articles (products) containing substances of very high concern (SVHCs) in concentrations above 0.1% weight by weight must inform ECHA and consumers about the presence of these SVHCs. This information can be communicated to consumers through the supply chain, often in the form of Safety Data Sheets (SDS) and communication with suppliers.

2. **Authorization and Restriction:** Some chemicals used in products may be subject to authorization or restriction under REACH. If a chemical used in a product is restricted or requires authorization, manufacturers and importers of the product must ensure compliance and may need to seek authorization or find suitable alternatives.

3. **Supply Chain Communication:** Under REACH, there is a requirement for communication of information about the safe use of chemicals in the supply chain. This includes sharing information on the safe handling, storage, and use of chemicals in products.

4. **Substitution of Hazardous Substances:** REACH encourages the replacement of hazardous substances in products with safer alternatives when feasible. Manufacturers may need to consider alternative chemicals or formulations to ensure compliance with REACH requirements.

Furthermore, from Article 2, REACH considers safety, health and environmental matters including the following directives (EUR-Lex, n.d.):

(a) Council Directive 89/391/EEC of 1989, focusing on the implementation of measures to promote enhanced safety and health conditions for employees during their work.
(b) Council Directive 96/61/EC of 1996, concerned with integrated pollution prevention and control.
(c) Directive 98/24/EC and Directive 2000/60/EC of European Commission of 2000 outlining a framework for the community's actions related to water policy.

3.4.2 POP Regulation Annex I (Regulation (EU) 2019/1021)

As mentioned in section 3.3.2, POPs are class of hazardous chemical compounds with a potential of transcending national borders, commonly exist at significant distances from their original sources of release, have long-lasting environmental persistence, accumulate in biological systems, and thereby present a peril to both human health and the ecosystem (EUR-Lex, n.d.). Hence, it is important to control the manufacturing, placement in the market and use of products with these POPs. Annex I of Regulation (EU) 2019/1021 concerning POPs provides a comprehensive list of substances subject to various restrictions within the EU. The substances listed in Annex I of Persistent Organic Pollutants (POPs) entails a comprehensive ban on their production, introduction into the market, and utilization. (EUR-Lex, n.d.)

The substances listed in Annex I are categorized into three groups (Stockholm Convention):

- **Group I:** This category comprises substances that were originally listed in Annex A to the Stockholm Convention on Persistent Organic Pollutants before July 15, 2019. Examples include aldrin, chlordane, dieldrin, endrin, heptachlor, hexachlorobenzene, mirex, toxaphene, polychlorinated biphenyls (PCBs), polychlorinated dibenzo-p-dioxins (PCDDs), and polychlorinated dibenzofurans (PCDFs).

- **Group II:** Substances in this group were added to Annex A or B of the Stockholm Convention on Persistent Organic Pollutants on or after July 15, 2019. Examples include chlordecone, hexabromobiphenyl, pentachlorobenzene, perfluorooctane sulfonic acid (PFOS) and its derivatives, tetrabromodiphenyl ether and pentabromodiphenyl ether (commercial octa-BDE), hexabromodiphenyl ether and heptabromodiphenyl ether (commercial penta-BDE), pentachlorophenol and its salts and esters (PCP), hexachlorobutadiene (HCBD), decabromodiphenyl ether (commercial deca-BDE), short-chain chlorinated paraffins (SCCPs), and hexabromocyclododecane (HBCDD).

- **Group III:** Substances in this category are not specifically listed in Annex A or B of the Stockholm Convention on Persistent Organic Pollutants. However, they are included in Annex I to the Protocol associated with the 1979 Convention on Long-Range Transboundary Air Pollution regarding Persistent Organic Pollutants. Examples here include polycyclic aromatic hydrocarbons (PAHs).

The prohibition applies regardless of whether these substances are in their pure form, included in preparations (as mixtures), or as elements of products. However, there are certain exemptions depending upon the maximum permissible concentration and application of use. According to the Article 4, the substances used for laboratory-scale research or as reference standards are exempted from control measures. Furthermore, the measures are not applicable to a substance found incidentally as an unintended, minute impurity in substances, mixtures, or articles. (EUR-Lex, n.d.)

In addition to that, it is the responsibility of a Member State if they intend to allow production of a substance listed in Part A of Annex I and use it as a closed-system site-

limited intermediate until the specified deadline. However, this notification is permissible only if certain conditions are met (EUR-Lex, n.d.):

(a) An annotation in the relevant Annex explicitly permits such production and use of the substance.
(b) The manufacturing process should convert the substance into one or more other substances that do not exhibit the characteristics of a persistent organic pollutant.
(c) It should be demonstrated that during the production and use of the substance within a closed system, there will be no significant exposure of humans or the environment to the substance. This must be substantiated through an assessment of the closed system, following the guidelines outlined in Commission Directive 2001/59/EC.

The notification should also be communicated to other Member States and the Commission. It should contain information about the actual or estimated total production and use of the substance in question, along with details about the closed-system site-limited process. Additionally, it should specify any residual amounts of persistent organic pollutant starting material that unintentionally contaminate the final product. (EUR-Lex, n.d.)

Overall, Annex I of the regulation establishes a comprehensive framework for the management and control of these substances within the EU, considering their origin, international agreements, and their categorization based on their associated risks.

3.4.3 CLP (Regulation (EC) No 1272/2008)

The Classification, Labelling and Packaging (CLP) Regulation, (EC) No 1272/2008, is meant to protect health and environment, while ensuring free movement of substances, mixtures, and articles (ECHA, Understanding CLP, n.d.). It is an amendment to the previous Dangerous Substances Directive (67/548/EEC (DSD)), the Dangerous Preparations Directive (1999/45/EC (DPD)) and Regulation (EC) No 1907/2006 (REACH). Currently it is the only regulation in force for classification and labelling of substances and mixtures in EU. CLP applies to all industrial sectors and requires manufacturers, importers or downstream users of substances or mixtures to classify, label and package their hazardous chemicals appropriately before allowing them on the market (ECHA, Understanding CLP, n.d.).

The key aim of CLP is to assess substances or mixtures and evaluate if they have properties that could lead to a hazardous classification. It considers classification as the starting point for all hazard communication (ECHA, Understanding CLP, n.d.). CLP includes several classification criteria which can be used to assign each substance or mixture with an appropriate hazard class and category including guidance on to how to do this. The hazard classes in CLP cover physical, health, environmental and additional hazards. The identified hazards are communicated across the whole supply chain through hazard labelling. The labelling allows for efficient communication of the hazard classification to the user of a substance or mixture to alert them about the presence of a hazard and communicate the need to manage any associated risks.

In addition, CLP defines the criteria for labelling elements. These are set for each hazard class and category and include pictograms, signal words and standard statements for hazard, prevention, response, storage and disposal (ECHA, Understanding CLP, n.d.). The CLP also includes general packaging standards for safe transit of hazardous substances and mixtures and is used as the basis for legislative provisions on the risk management of chemicals. Poison centres, C&L inventory held by European Chemicals Agency (ECHA), alternative names in chemical mixtures and harmonized classification and labelling are also part of CLP. An exhaustive list of harmonized classifications can be found from the Annex VI of the CLP Regulation (ECHA, Table of harmonised entries in Annex VI to CLP, n.d.).

3.4.4 Food contact legislation (Regulation (EC) No 1935/2004)

The most current regulation related to food contact materials (FCM) legislation in EU is the Regulation (EC) No 1935/2004 (Consolidated), which is the updated version of the earlier EC regulation No 1935/2004. The regulation provides general principles to ensure safety and inertness for all food contact materials in Europe (Commission of EU, n.d.). The regulation states that materials that are in contact with food substances must not release any substances into the food that they are in contact with at such levels that could be harmful to humans and that they do not chance the composition, taste or colour of the food.

In addition to this, the food contact materials must be manufactured according to the Good Manufacturing Practices (GMP) (Commission Regulation (EC) No 2023/2006). The GMP regulation aims to ensure that the manufacturing processes for materials intended for food contact are well controlled so that materials comply with the FCM legislation. The GMP regulation states that the manufacturing premises must be fit for purpose and staff be aware of every critical production stage. It also requires for the documentation for quality assurance and quality control systems to be maintained properly, and that suitable materials are selected from the start so that the requirements of the final product are met. The rules set in the GMP regulation apply throughout the manufacturing chain of food contact materials.

Also, there are specific EU legislations that guide the use of certain materials that may come into food contact. These legislations are, for example Epoxy Derivates (EC) No 1895/2005, Plastics (EC) No 10/2011, Recycled Plastics (EC) No 2022/1616, BPA (EC) No 213/2017, Active and Intelligent Materials and Articles (EC) No 450/2009 and Import Restrictions from China and Hongkong (EC) No 284/2011 (Commission of EU, n.d.; Authority, n.d.)

From the plastic recyclate point of view the most relevant regulation is the Regulation (EU) No 2022/1616 on recycled plastics. On 10th October 2022, Regulation (EC) No 282/2008 on recycled plastic materials and articles intended to come into contact with foods, was repealed by Regulation (EU) No 2022/1616 broadening its original scope. In the last decade, the plastics recycling industry introduced a variety of new processes and techniques to recycle plastics intended to come into contact with foods. The progress achieved by the industry outpaced the narrow legal framework of Regulation

(EC) No 282/2008, to a point where new approvals could no longer be granted being outside the framework to assess the safety of such recycling processes.

Regulation (EU) No 2022/1616 on recycled plastic materials and articles intended to come into contact with foods lays down rules on:

- the placing on the market of recycled plastic food contact materials,
- the development and operation of recycling processes producing recycled plastic to be used in contact with foods,
- the use of recycled plastics intended to come into contact with foods,
- the manufacture of materials and articles in which recycled plastic is used behind a functional barrier.

It introduces two pathways to obtain approval for food contact materials: the suitable technology addressing already evaluated processes, and the novel technology addressing processes that have not been assessed yet.

3.4.5 RoHS (Directive 2002/95/EC and 2011/65/EU)

Restriction of Hazardous Substances in electrical and Electronic Equipment (RoHS) directive is divided into two directives 2002/95/EC, often referred to as RoHS 1 and 2011/65/EU, referred to as RoHS 2. The RoHS 2 directive is a recast for the RoHS 1 directive and some of the main additions in it are, for example clarification of some definitions, extending the requirements to all EEE and offering a methodology to assess new hazardous substances in EEE. The RoHS 2 directive aims to develop better regulatory conditions, increase the level of legislative clarity and certainty, adapt the directive to technical and medical processes, aligning the RoHS with other EU legislation and prevent risk to human health in EEE waste management (Commission of EU, 2012).

Together the RoHS Directives aim to prevent and reduce risks on human health and the environment that are related to electronic and electrical waste. To achieve this the directive restricts the use of certain hazardous substances that could be substituted by safer alternatives used in EEE. Some equipments are excluded from the RoHS restrictions, such as active implantable medical devices, pipe organs and large-scale stationary industrial tools, but the currently restricted substances are:

- lead
- cadmium
- mercury
- hexavalent chromium
- polybrominated biphenyls (PBP)
- polybrominated diphenyl ethers (PBDE)
- bis(2-ethylhexyl) phtalate (DEHP)
- butyl benzyl phthalate (BBP)
- dibutyl phthalate (DBP)
- diisobutyl phthalate (DIBP)

The directive sets a maximum concentration value for the restricted substances which must not be exceeded. This value is 0,01 w-% for cadmium and 0,1 w-% for the rest of the substances. By restricting the use hazardous substances, the directive also promotes the recyclability of EEE and is, thus, closely linked to the WEEE Directive. From plastics recycling perspective, the brominated flame retardants, for example, which have been used in some EEE pose a problem as they may not be compliant with RoHS guidelines. These flame retardants often include PBDE, which is on the restricted substances list. The key aspect in this case is to how to control the consistency of the recycled plastic so that it does not exceed the 0,1 w-% limit set in RoHS directive.

3.4.6 Ecodesign Directive (2009/125/EC)

The Regulation is horizontal in nature, covering all products being placed on the market. There are two set of measures that describe the proposal, one on products' requirements and the other on information products have to bear. On the former, recyclability and recycled content are generically included to define that products must be well managed at the end of their life, but the proposal does not go into the details. Vertical measures are expected to follow this proposal, via secondary legislation focused on products/group of products.

In particular, under the Commission's proposed text, the Regulation would address the design of every product placed on the EU market in order to make such products more durable, reliable, reusable, upgradable, reparable, easier to maintain, refurbish and recycle, and energy and resource efficient.

The proposal would ensure that better environmental sustainability information for consumers and supply chain actors is provided by introducing a Digital Product passport that will make repairability and recyclability of products easier, while also ensuring better tracking of substances of concern along the supply chain.

As such, the proposal aims at introducing requirements not only for energy efficiency but also for circularity and reduction of the environmental footprint of products.

Furthermore, the proposal would also empower the Commission to introduce a ban on the destruction of unsold goods, with some expectations, and mandatory requirements for green public procurement.

Directive 2009/125/EC lays down general rules on Ecodesign criteria that are then set for specific product groups in implementing measures. These implementing measures set out precise Ecodesign requirements and energy consumption criteria for sectors of energy-consuming and energy-related products.

4 BARRIERS HINDERING PLASTIC CIRCULARITY IDENTIFIED IN THE CURRENT LEGAL FRAMEWORK

4.1 Key barriers referenced in literature

Overlapping regulations and frequent updates can be considered as a barrier that is hindering or prohibiting recycling effort in plastics. For example, most plastics recycling needs to comply with REACH, as stated previously, but exemptions can be applied for and granted for justified reasons. However, the exemptions are in some cases undone by changes in the SVHC (substances of very high concern) list (Jepsen;Reihlen;Wirth;& Sander, 2012). This means that even if one has been granted an exemption from the REACH but the recyclate contains over 0.1% of substances that are identified as SVHC after the exemption was granted, one must apply for another exemption (Wagner & Schlummer, 2020). This can be a very lengthy process and lead to loss of revenue during the application period. The Globally Harmonized System of Classification and Labelling of Chemicals (GHS) regulation update (Council of the EU, 2017), on the other hand, lead to the rejection of the whole plastic waste stream (Wagner & Schlummer, 2020).

In addition, unclear descriptions of actions and requirements can be seen as a barrier. For example, the level of BFR DecaBDE and other PBDEs should be less than 1000 ppm (Council of the EU, 2019) in recycled plastics but this cannot directly be measured from the recycled streams (Wagner & Schlummer, 2020). What can be measured is the bromine content, which is present in BFR (brominated flame retardants) but does not fully represent the exact amount of the flame retardants present. Also, the accuracy of identification methods for bromine is a question, which is why levels <2000 ppm are considered “bromine free” in recycled streams (Goodship (Ed.), 2012). A clear link between the measured bromine content and allowed POP-BFR and POP-PBDEs levels is missing from the directive, which can lead to reduced yield and revenue from recycled plastics (Wagner & Schlummer, 2020).

Also, over ambitious goals, such as in the packaging waste legislation (Council of the EU, 2018), can lead to difficulties in the plastic waste sector. The legacy additives and tight SVHC limits can lead to over sorting in waste management and high rejection rates from recycling (Wagner & Schlummer, 2020). This does not improve circularity as intended but rather can increase the amount plastics going to incineration.

4.2 Barriers from interviews and workshops

To identify the barriers and actions to leverage plastic waste to product interface in practices, 12 interviews were conducted with key stakeholders in the plastic recycling industry. The interviewees were asked to provide their insights on the challenges and potential resolutions to uptake recycled plastic for product manufacturing with legal aspect in focus. Additionally, a workshop titled "Plastic Waste to Product Interface - Barriers and Opportunities" was held. The workshop created a forum to review the current legal frameworks surrounding of plastic waste to product, gather inputs and validate the barriers and opportunities identified in the interviews with the larger stakeholder group in plastic recycling.

The results of interview and workshop were divided into 6 main stages of plastic waste to product including collection, sorting, recycling, converting, article manufacturing and life service. The identified barriers are summarised in Table 3 and the potential solutions are presented in

Table 4.

Table 3. Identified barriers of plastic waste to product interface

	Interview	Workshop
Collection	• Lack of end-of-waste criteria for plastic waste • Illegal and substandard practices in the management of waste • Low collection rate leading to landfill and other undocumented disposal	• Unharmonised collection system in EU • Illegal and substandard practices in the management of waste • Unambitious collection rate target
Sorting	• Mixing of different plastic waste groups before or after shredding causing non-homogeneity streams	• Manual and labour-intensive separation methods, lack of automation • Black plastics (dark color make them difficult to sort) • Lack of recycling codes for bioplastics and other engineered plastics • Stream quality affected by multimaterial and multilayer objects
Recycling	• Constant changing chemical limit and legislation holding back investment and increasing risks • Lack of alignment between design and end-of-life management • Unharmonised legislations, lack of unified set of definitions in different legal acts • Lack of standardised procedures and technical guidelines • Conflict between complying technical limit of chemical legislations (POP, REACH) and achieving ambitious recycled content targets (plastic strategy, chemical strategy, waste framework directive)	• Ununified legislative targets through the value chain that burdens the end-of-life management • Chemical recycling is not accepted as recycling in legislation • Untapped potential of mechanical recycling • Complicated process due to polluted stream (e.g. by additive) • Lack of technical guidelines for plastic waste sampling and for detecting and testing regulated substances (e.g. POPs, BFR) • Variations in legislation and requirements between countries • Lack of incentive and high cost of recyclates comparing to new materials

	• Perception of close-loop recycling limiting the availability and use of recycled plastic in other applications than its original manufacturing • No single market for recyclates • Higher price of recycled plastic comparing to virgin plastic	
Converting	• Impurities of recycles which can be linked to low quality of collection and recycling process • Non-homogeneity of material stream • Ecodesign regulation does not cover the impact assessment of recycling process • Deterioration of quality in the process of converting • Treatment of rejected plastic needed	• Microplastic generation • Underdeveloped infrastructure to process recyclates • Possibility of producing higher CO2 footprints and Embodied Energy Consumptions • Recylates quality affected by collected stream substances
Article manufacturing	• Unstable supply and demand of recylates • Misconception of recycled plastic as low quality • Insufficient availability of qualified plastic recyclate to produce components for compliance with product regulations • Increase the recycled content in new product at fast pace increases the risk of harmful substance control at the same pace	• Gap between the design of the products and the possibilities of effective recycling • Lower properties of recyclates and lack of high-quality recyclates availability • Understanding of additives behavior with recyclates needed • Legislation hindering the use of recycled plastic in high performance product (e.g. in construction) • Processes need to be updated to uptake recyclates
Life service	• Lack of effectiveness and performance of the Extended Producer Responsibility schemes • Lack of communication between the actors within the value chain • Need for improvement of product information registration	• More support for repairing and maintenance before recycling needed • Need of accepted test methods to generate data on end of life (EOL) of plastic products with additives

Six stages of waste to product interface present significant obstacles to achieving a sustainable and efficient circularity.

In the collection phase, issues such as the absence of clear end-of-waste criteria for plastic waste, illegal disposal practices, and low collection rates contribute to the prevalence of landfill and undocumented disposal. Sorting proves problematic due to the mixing of different plastic waste groups, leading to non-homogeneous streams, as well as the labor-intensive nature of separation methods, lacking automation.

Recycling is hindered by constantly changing chemical limits and unharmonised legislations, causing hesitancy in investment and increasing gap between complying technical limit of chemical legislations (POP, REACH) and achieving ambitious recycled content targets (plastic strategy, chemical strategy, waste framework directive).

Converting faces challenges from impurities in recyclables linked to collection and recycling process quality, material stream non-homogeneity, and the possibility of causing higher environment impact from the entire recycling process. In article manufacturing, an unstable supply and demand of recyclate, misconceptions about recycled plastic quality, and insufficient availability of qualified plastic recyclate for compliance with product regulations pose significant dilemma.

The high cost of recyclate comparing to virgin material is a key hinderance for its utilisation. In addition, a lack of alignment between effective design for end-of-life management, and the absence of standardized recycling procedures and technical guidelines to measure regulated substances (POPs, BFR) impede the recycling process. Furthermore, the narrowness of close-loop perception in recycling limits the availability and use of recycled plastic in other applications than its original manufacturing.

Finally, in the life service stage, challenges persist, including the need for more effective Extended Producer Responsibility (EPR) schemes, enhanced communication within the value chain and improved product information registration.

Notably, legislative intervention holds the potential to address technical challenges through mandates for circular design and the restriction or prohibition of challenging-to-recycle materials and compositions like black plastic and harmful chemicals.

5 ACTIONS TO BOOST THE UPTAKE OF RECYCLATES

Through the interview insights and collaborative workshop validation,

Table 4 provides an overview of the potential actions to overcome the barriers and boost the uptake of plastic recyclates.

The proposed solutions for waste to product interface encompass a comprehensive technical and legislative approach across various stages of the recycling process.

Beginning with collection, incentives and refined end-of-waste criteria aim to improve waste separation and monitoring. In sorting, clear polymer labelling and advanced sorting processes are suggested to enhance efficiency. For recycling, a stable and harmonised legislative framework is advocated. Leveraging existing legislation like WEEE (Waste Electrical and Electronic Equipment Directive), REACH (Registration, Evaluation, Authorization and Restriction of Chemicals), RoHS (Restriction of Hazardous Substances Directive), POP (Persistent Organic Pollutants) and ESPR (European Strategy for Plastics in a Circular Economy) can help establish a robust connection between waste and product regulations, along with the development of specific end-of-waste criteria for plastics in WFD (Waste Framework Directive).

Expanding closed-loop recycling applications and implementing carrot and stick approach of tax incentives for recycling and using recyclates and tax burden for the opposite further bolster recycling efforts.

In converting, investments in technology and depolluted processes are highlighted to ensure high-quality recyclate. Article manufacturing can be enhanced through legislation focusing on recyclability, ecodesign criteria, and a secure supply of qualified recyclate. In the life service stage, consumer awareness, clear recyclability labelling, and collaboration among stakeholders are emphasized, along with extended producer responsibility. Additionally, a robust product information registration system and non-competing legislation supporting a circular waste hierarchy are crucial. Providing more fundings for entire waste plastics management underpins the paradigm shift from waste to product.

Table 4. Action to boost plastic waste to product interface

	Interview	Workshop
Collection	• Improve separate waste collection system and its monitoring with incentives • Improve end-of-waste criteria for proper EOL plastic management	• Enhance communication with EU Member States and policy makers • Create white paper for collection system development • Extending producer responsibility for end-of-life management
Sorting	• Plastic products must have clear sign of the type of the polymers • Prevent mixing of different plastic categories • More dedicated sorting processes • Funding for research and development	• Design for easy dismantling and recycling mandatory by legislation • Artificial intelligence (AI) and automation development • Replacement of carbon black pigment used in plastic products • Assigning recycling codes for specialised plastics • Funding for research and development
Recycling	• Creating a stable and harmonised legislative environment • Leveraging WEEE, REACH, RoHS, POP, ESPR to establish strong link between waste and product legislations • Expansion of close-loop recycling in versatile applications other than its original manufacturing usage • Tax incentive for use of recylates and increase tax for unrecyclable practices • Funding for research and development	• Mandate design for recycling by legislation • Create harmonised guideline, standards and legislations (e.g. change of ppm levels of allowed POP containing waste or provide detection method guideline) • Possibility for reuse before recycling • Funding for research and development
Converting	• Investment in technology and reduction of inadequate depollution of the material stream	• Process optimization for sustainability • Apply eco-auditing and life cycle assessment (LCA) methodology for CO2 monitoring

	• Upgrade recyclate quality with additives to be comparable to virgin material of industrial quality • Remove contamination through the clean mechanical recycling process • Chemical recycling plays critical role in treating low value plastics	• Funding for research and development
Article manufacturing	• Legislation focusing on recyclability of the product and recycling process sustainability (goals for the material recycling, limiting single-use plastics) • Ecodesign for recycling criteria (mono-material, recycled content, sustainable additives) • Ensure supply security of qualified recyclate before enacting regulatory environment that increases its demand	• Regulation on recyclate content • Incentives for using recyclate, higher taxes for using virgin plastics • Proper alignment between different legislations, identification of bottlenecks and conflicts • Funding for research and development
Life service	• Improve consumer awareness, build knowledge about recycled plastics • Labelling for recycled product identification and claim • Multidisciplinary collaboration and communication from the design to end-of-life phases between actors • Extend producer responsibility and share of responsibility across the value chain • Enhance the product information registration system reflecting new sustainability content requirement from the legislations	• Non-competing legislation to support cascading approach to the circular waste hierarchy • More and efficient funding options focusing on EoL waste plastics management

6 CONCLUSIONS

6.1 Solving the barriers with the identified solutions

Addressing the complex challenge to significantly increase the recycling of plastic waste into new and also value-added products requires multifaceted solutions that involve stakeholders across the value chain. Table 5 presents the matching of identified barriers in chapter 4 and its potential solutions in chapter 5 through a breakdown of the key stages in the plastic waste to product interface. Each solution is tailored to tackle specific challenge, with the ultimate goal of fostering a more sustainable and efficient plastic waste to product transformation.

Table 5. Solving the barriers with identified solutions

	Barriers	Solutions
Collection	Lack of end-of-waste criteria for plastic waste management	Improve end-of-waste criteria for proper EOL plastic management
	Low collection rate leading to landfill and other undocumented disposal	Improve separate waste collection system and its monitoring with incentives
Sorting	Mixing of different plastic waste groups before or after shredding	Plastic products must have clear sign of the type of polymers
	Manual and labour-intensive separation methods, lack of automation	Design for easy dismantling, AI and automation sorting development
	Black plastics	Replacement of carbon black pigment used in plastic products
Recycling	Constantly changing chemical limits and legislations hindering investment	Creating a stable and harmonized legislative environment
	Conflict between complying technical limit of chemical legislations (POP, REACH) and achieving ambitious recycled content targets (plastic strategy, chemical strategy, waste framework directive)	Leveraging WEEE, REACH, RoHS, POP, ESPR to establish strong link between waste and product legislations
	Lack of alignment between design and end-of-life management	Mandate design for recycling by legislation
	Perception of close-loop recycling limiting the availability and use of recycled plastic	Expansion of closed-loop recycling in versatile applications other than its original manufacturing usage
	Higher cost of recyclates comparing to virgin material	Tax incentive for recyclable practice and tax burden for the opposite

Converting	Impurities of recyclables linked to low quality of collection and recycling process	Investment in technology innovation to prevent non-homogenous and polluted material streams
	Deterioration of material stream quality in the converting process	Upgrading recyclates with additives, research and development
	Possibility of higher environment impact from the converting process	Development of eco-auditing, LCA for performance optimization
Article Manufacturing	Gap between the design of the products and the possibilities of effective recycling	Legislation focusing on recyclability of the product and recycling process sustainability (eco-design for circularity, mono-material, recycled content target, material recycling target, sustainable additives)
	Misconception of recycled plastic as low quality	Improve recyclate quality to be comparable to virgin material of industrial quality
	Insufficient availability of qualified plastic recyclate	Ensure supply security of qualified recyclate before enacting a regulatory environment that increases its demand
Life Service	Lack of effectiveness and performance of Extended Producer Responsibility schemes	Extend producer responsibility and share of responsibility across the value chain
	Lack of communication between the actors within the value chain	Multidisciplinary collaboration and communication from the design to end-of-life phases between associated actors
	Need for improvement of product information registration, labelling for recyclable claim	Enhance the product information registration and eco-labelling system reflecting new sustainability content requirement from the legislations
	More support for repairing and maintenance before recycling needed	Non-competing legislation to support cascading approach to the circular waste hierarchy

The plastic waste to product interface faces a range of challenges at various stages. In the collection phase, issues arise from the lack of clear end-of-waste criteria and low collection rates. Solutions include improving end-of-waste criteria and implementing incentives for enhanced waste collection systems. Sorting encounters problems like mixing different plastic waste groups and labor-intensive separation methods. To address this, solutions focus on clear polymer labeling, automation, and AI advancements.

Recycling confronts obstacles from changing chemical limits and complex legislation, which can be eased by creating stable legislative environments and establishing connection between waste and product legislation. Converting stages deal with impurities and non-homogeneity of material streams, addressed through technology investments and process optimization. Article manufacturing contends with challenges such as design for recycling limitations, misconceptions about recycled plastic quality and unstable supply of qualified recylates. Solutions involve legislation to enhance product recyclability by desing, tax incentive for recylate usage and technological innovation to upgrade recyclate quality.

In the life service stage, issues related to lack of communication and product information registration across the value chain are tackled through improved awareness, multidisciplinary collaboration and development of information sharing and labeling systems. Furthermore, support for cascading value, repair and maintenance is emphasized, along with legislation to promote circular waste management.

6.2 Unsolved barriers for future development

Throughout the alignment of identified barriers and solutions, certain challenges persist. The identification of unresolved challenges underscores the critical need for future development to leverage plastic waste and product interface. The summary of these unsolved barriers is presented in Table 6.

Table 6. Unsolved barriers for continuous development

	Unsolved barriers
Collection	• Illegal and substandard practices in the management of waste
Sorting	• Mixing of plastic wastes causing non-homogeneity stream for recycling
Recycling	• Conflict between complying technical limit of chemical legislations and achieving ambitious waste recycling targets • No single market for recyclates
Converting	• Treatment of rejected plastics needed • Microplastic generation
Article manufacturing	• Insufficient availability of qualified recyclate to produce components for compliance with product regulations
Life service	• Need of accepted test methods to generate data on EOL plastic products with additives

The future development of waste to product interface presents remaining unresolved barriers spanning the entire lifecycle, from collection, sorting, recycling to converting, manufacturing and life service.

Uncollected, illegal and substandard waste management practices pose significant environmental and health risks. The mixing of different plastic waste groups, leading to non-homogeneous recycling streams, hampers the efficiency of sorting and further recycling processes.

Balancing compliance with strict chemical legislations against ambitious recycling targets remains a complex recycling issue. The absence of a unified market for recyclates creates instability for recycling facilities. Finding effective treatment methods for rejected plastics and microplastic generation during converting process is crucial.

The scarcity of high-quality recycled plastics meeting regulatory standards hinders sustainable manufacturing. Considering the life service, the lack of standardized test methods for evaluating the end-of-life behavior of plastic products with additives complicates the informed decision-making about the use and disposal of plastic products.

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