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DigInTraCE

DIGITAL VALUE CHAIN INTEGRATION TRACEABILITY FRAMEWORK FOR PROCESS INDUSTRIES FOR CIRCULARITY AND LOW EMISSIONS BY WASTE REDUCTION AND USE OF SECONDARY RAW MATERIALS

D5.1

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DigInTraCE

A Digital value chain Integration Traceability framework for process industries for Circularity and low Emissions by waste reduction and use of secondary raw materials

Legal Disclaimer

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List of abbreviations

Abbreviation	Definition
EU	European Union
WEEE	Waste electrical and electronic equipment
EEE	Electrical and electronic equipment
ABS	Acrylonitrile butadiene styrene
PP	Polypropylene
HIPS	High impact polystyrene
PC	Polycarbonate
FR	Fire Retardants
BFRs	Brominated flame retardants
SRM	Secondary raw material
OSB	Oriented strand board
FSC	Forest Stewardship Council
UF	Urea-formaldehyde
PF	Phenol-formaldehyde
MF	Melamine-formaldehyde
EEA	European environmental agency
C&D	Construction and demolition waste
WFD	Waste framework directive
VOC	Volatile organic compounds
CCA	Chromated copper arsenate
MSW	Municipal solid waste
IED	Industrial emissions directive
BAT	Best available technique
p-MDI	Polymeric methylene diphenyl diisocyanate
PUR	Polyurethane
PS	Polystyrene
PVC	Polyvinyl chloride
PC/ABS	Polycarbonate and acrylonitrile butadiene styrene
PMMA	Polymethyl methacrylate
CPR	Construction products regulation
GPP	Green public procurement
SVHC	Substances of very high concern
ECHA	European Chemicals Agency
BPA	Bisphenol A
HMF	Hydroxymethylfurfural
LoW	European List of Waste

1. Introduction

The present report constitutes deliverable 5.1 “Secondary materials quality characterization for recycle, reuse upgrade” within the framework of the DigInTraCE project. The following activities refer to WP5 “Technologies for secondary materials upgrade and process optimization” and specifically to task 5.1 “Secondary materials quality characterization for recycle, reuse and upgrade (per value chain analysis)”.

WP5 aims to achieve three main objectives, the first of them is to characterize the secondary material of the new value chains, for which the outputs of T5.1 are crucial.

The objective of this report is to analyse four different sectors (polyester, wood, resins and plastics) among EU and national regulations to check whether secondary markets are suitable, and to provide potential pathways and main actors based on recycling/reuse and upcycling opportunities. To achieve this, the following activities have been carried out as part of T5.1:

- Consulting the demos to obtain accurate information on their waste and value chains.
- Identifying and compiling all applicable legislation among EU and national regulation, quality requirements and relevant information.
- Developing a methodology that allows the analysis of the different sectors in a homogeneous way.
- Assessing the four different sectors and comparing their current status based on the evaluation criteria applied.
- Proposing possible pathways and main actors based on recycling/reuse and upcycling opportunities for each case.

This deliverable reports on the results of the above-mentioned activities in relation to the assessment of the suitability of the secondary raw materials market for the above-mentioned sectors. Recommendations and views to support their development, as well as comparisons between the sectors, are also discussed at the end of this document.

2. Regulatory assessment methodology

For the analysis of the adequacy of secondary raw material (SRM) markets from a regulatory perspective to produce a comparable result across the four sectors, a set of criteria were applied which, depending on the state of the regulatory framework of the market, were assigned a value between three or four options depending on the criterion.

These criteria are derived from an EEA report in which an assessment framework to describe the functionality of existing SRM markets is developed. Given the scope of T5.1, only those related to the regulatory framework were used, resulting in 5 criteria, these being:

- Non-policy-driven supply and demand.

  Assess if the market can survive economically even without waste policies that exogenously push demand and/or supply or modify prices through, for example, taxes and subsidies.

- Included in compliance schemes for packaging waste or extended producer responsibility schemes.

  Assess if the material is involved in closed-loop circular schemes (voluntary or policy target-driven) that enlarge the demand and supply and then favour the stability and growth of the SRM market.

- No competition from energy use.

  Assess if the SRM material is not subject to competing demand from energy recovery operations that can enlarge the market but (especially for a stable supply) can also displace the SRM market.

- Product specifications are standardised.

  Assess if the SRM is subject to agreed or formal (regulatory) definitions and standards that are accepted and recognised by operators as references for contracts and transactions.

- No regulatory barriers to using SRMs as inputs in manufacturing.

  Assess if the SRM is not subject to adverse or discriminatory regulatory provisions for its use as an industrial commodity. Moreover, assess if it is not subject to regulatory difficulties or barriers, for example in the end-of-waste process.

In summary, after having analysed each of their regulatory frameworks, each of the sectors has been assessed on the basis of these criteria (which have been considered as equally important), assigning a value according to the status of the sector according to the corresponding criterion, as shown in the Annex I, and summing the resulting values to get a final score averaged per sector. This value was then used to assess the state of the sector, considering that in cases where the value was between 0 and 1 the SRM market was not very functional, between 1 and 2 it was average, and between 2 and 3 it was very functional.

3. Initial characterisation of waste

This section presents a preliminary description of each of the waste streams studied in the DigInTrace project, in order to provide a basic characterisation that will be used as input for the study of the regulations related to each type of waste, as well as the identification of potential pathways for reuse, recycling and upcycling. The basic information on the waste streams has been obtained by direct interaction with the project partners. Importantly, it should be noted that a more exhaustive characterisation of the different waste streams will be carried out later in the project (WP5 and WP6) and will identify their composition, granulometry, etc., as well as evaluate valorisation routes and their integration into circular value chains in each of the four sectors addressed in the project.

- Polyesters:

  In the framework of DigInTrace, polyesters (mainly PET) decontamination and upcycling will be evaluated. Post consumer PET recycling will be performed, and the produced recycled polyester will be processed into fibres, targeting particularly high tenacity yarns, which are valuable for technical applications such as roofing elements, conveyor belts, seat belts, membrane structures, among others.

- Wood:

  In the framework of this project, wood by-products will be valorised in the manufacture of furniture. Specifically, the wood by-products consist of wood chips and sawdust, both derived from pure material of different sizes (from original trestles and from furniture manufacturing). These secondary raw materials are free of contamination and impurities, as they come directly from primary processing.

- Resins:

  In the framework of this project, novel, more sustainable phenol-formaldehyde (PF) resins will be prepared by incorporating waste from agroindustry’s in their formulations. In detail, the phenol component of the resin will be partially replaced by proteins extracted from oilseed cakes, which are pressed plant materials left after the production of vegetable oils. The oilseed cakes will be subjected to different extraction methods, targeting the isolation of proteins in high yields and using green solvents and energy-efficient processes. The incorporation of proteins in the PF resins will be optimized to achieve maximum phenol replacement and the required properties of the final plywood panel.

- WEEE plastics:

  This project focuses on the use of mixed polymeric materials obtained from the recovery of waste electrical and electronic equipment (WEEE). The WEEE used is classified into three groups: Cold (refrigerators, freezers, air conditioners, etc.), Large household appliances (washing machines, dishwashers, ovens, etc.) and small household appliances (small electronic or digital appliances, lighting equipment, photovoltaic panels, etc.).

  The process starts with shredding the wastes and passing them through mechanical and magnetic screens to separate foreign materials like iron, powders, magnetic substances, glass, and paper. Flotation is then used to remove most of the metals and remaining materials from the plastics. Further cleaning involves removing wood, sponge, and rubber fragments through dry and wet flotation. The plastics containing flame retardants or with a density of 1.1 Kg/dm^3 are separated. Next, the plastic materials are ground to achieve homogeneity. In subsequent stages, separation by density takes place, with Polyethylene and Polypropylene floating as they are lighter, while HIPS/ABS sinks due to higher density. The dry line focuses on separating polystyrene and ABS from rubber residues and wood. Electrostatic separators divide ABS and HIPS, and a flotation tank divides HIPS with additives from pure HIPS. Lastly, a colour selection can be conducted for final sorting, primarily for "white HIPS" from the “Cool” group recycling.

4. EU and national regulation assessment of the selected sectors

4.1. Polyesters

4.1.1. Sector Overview

This section describes the status of the polyesters market and its application in several manufactured materials across Europe.

Polyesters are a type of polymer where the monomeric building blocks are linked by an ester chemical group. Polyesters are commonly used in a wide range of applications.

The most common polyester goods and derived products are found in the following sectors:

- Textiles: Two thirds of global clothing demand is met by synthetic textile fibers, with petro-based polyethylene terephthalate (PET) as the market leader industry. [1]
- Reinforcement materials: Polyester thermoplastics are used as binding resins in composite materials.
- Packaging: Polyesters are one of the main polymeric petro-based materials used for packaging moulding.
- Electronics: Due to its excellent electro-insulating properties, showing mechanical strength, thermal resistance, and ease in processing at the same time, polyesters are widely used engineering materials for electronics production.[2]

Regarding their synthesis, polyesters are formed by reacting a dicarboxylic acid (such as terephthalic acid) with a diol (such as ethylene glycol). The resulting polymer can be further processed into various forms, including fibers, films, and molded objects. Polyethylene terephthalate (PET), polybutylene terephthalate (PBT), and polytetramethylene terephthalate (PTT) are three of the main linear polyester materials synthesized from ethylene glycol or butylene glycol [3,4].

PET is considered the most extensively used polyester plastic. PET is used to make a wide range of products, including soda bottles, food containers, and polyester textiles due to its properties. PET’s durability, strength, and resistance to heat, chemicals, and moisture are the core of its superior properties. PET is also lightweight and can be easily processed using a variety of methods, including injection molding, extrusion, and blow molding [5]. The main properties of PET are described in the Table 1.

Table 1. Main properties of PET. Source: [6].

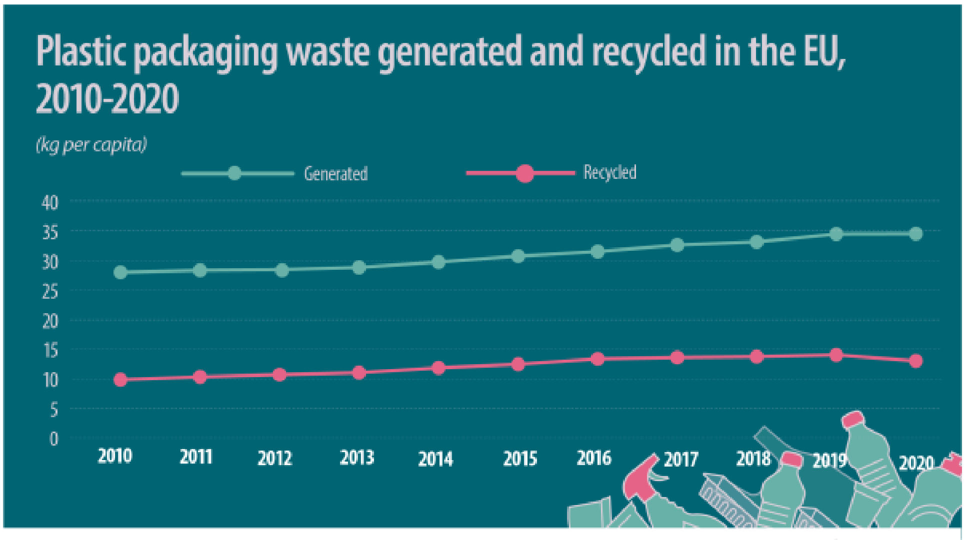
Main PET Features
PET is colourless and can be transparent (if amorphous) or translucent (if semi-crystalline). This is a very important characteristic as it allows consumers to see the content within the bottles.
PET is lightweight. The weight of a 1L PET bottle designed for containing water is 25 g. For comparison, a 750 mL wine bottle made with glass weighs 360 g, and a 500 mL aluminum container weighs 18 g.
PET is a thermoplastic, robust, semi-rigid to rigid, mechanically resistant to impact, and stretchable during processing.
PET shows gas-barrier properties against moisture and CO2.
PET is extremely inert compared to other plastics, and free from plasticizers.
To improve specific properties, PET can be blended with other polymers (e.g., with PC, PP, PP copolymers, and PBT) or surface-modified (through physical and chemical treatments).

Due to its multiple advantages, PET is extensively used worldwide, and its global annual production capacity reached approximately 30.5 million tons in 2019. Furthermore, this production is expected to increase to approximately 35.3 million metric tons by 2024 [7]. A drawback of PET is that it is not biodegradable and can persist in the environment for a long time. As a result, there has been a growing interest in developing more sustainable alternatives to traditional polyester plastics, such as biodegradable alternatives and novel efficient technologies for recycling.

Recycling pathways for PET are already found in industries, enabling further introduction into secondary markets. Plastic waste is often washed and sorted, so any hazardous substances and impurities are eliminated. Then, the plastic waste is usually shredded into small flakes which can undergo melting steps together at a high temperature to create uniform pellets. These pellets can be re-molded/extruded and thus used for end applications such as fibers, yarns, or other materials [8].

Polyesters in Packaging sector

According to PlasticsEurope [9], the European contribution to global plastic production reached 62 million tons (17% global production), whilst the packaging industry, which is the main relevant industrial segment, absorbed 40% of this demand.



2010, 2011 and 2020: data are estimated.

ec.europa.eu/eurostat

Figure 1: Packaging waste and recycling trends in the EU: Source: Eurostat

It is reported that the packaging of consumer goods is a recognized item in terms of its marketing value. Accordingly, packaging adds positive customer experience if it utilizes a good design, graphics, and information about its contents in the form of a label. In fact, nowadays industries use packaging not only to protect and cover products, but also as a tool to advertise and convey their brand to their customers.

Most popular materials used in the food industry for packaging are petroleum-based plastics (synthetic polymers). Such polymers include terephthalate (PET), low and high density polyethylene (LDPE and HDPE respectively), PP, PVC, and PS.

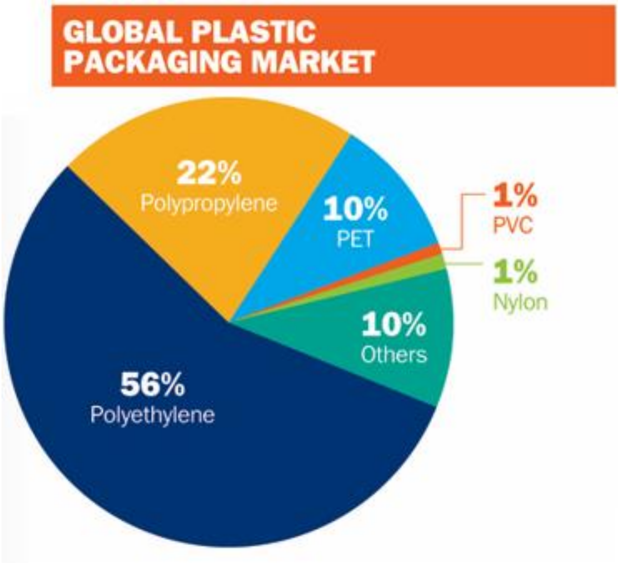


Figure 2: Global Plastic packaging market per type of plastic. Reproduced from source: Wood Mackenzie [10]

Polyesters for Reinforced Materials

Polyesters are extensively utilized resins, particularly in the maritime and automotive sectors. Composites used in sailing boats, yachts, and boats are predominantly constructed with this type of resin system, accounting for about 75% of total resin usage in the composites industry (Figure 3). This kind of resin consists of unsaturated polyester chains that can be either in liquid or solid state. These polyesters are cured into a thermoset when subjected to suitable conditions (typically pressure and temperature). In contrast, saturated polyester cannot be cured in this manner. As a result, unsaturated polyester resins are frequently referred to as "polyester resins" or simply "polyesters".

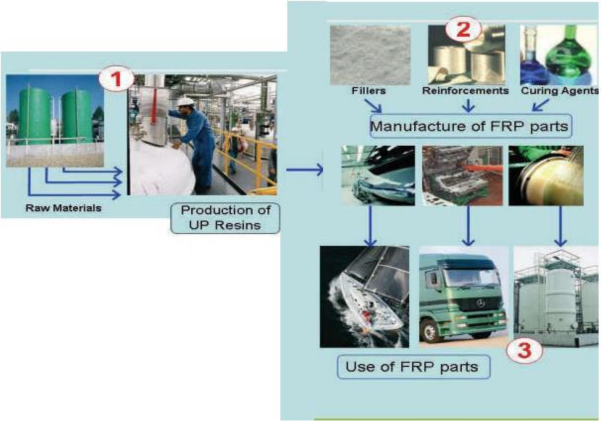


Figure 3: Polyesters in Fiber Reinforced Composites Valure Chain. Reproduced from [11].

Reinforced polyester materials are becoming increasingly popular in large construction and infrastructure projects due to their very low cost, ease of fabrication of large parts, and general strength and chemical inertness. They are used in chemically resistant containment vessels and their surroundings, particularly in the chemical industry. For recreation purposes, they are utilized in swimming pools and sailing, while in the transport industry, they are employed in large trucks and rail cars, with growing use in small trucks and parts for short run (specialty) automotives. In the electrical industry, polyester/glass fiber composites are of utmost importance due to their electrical insulation properties, which are utilized in a range of applications such as large and small junction boxes, light and electrical poles, and various switch gear applications.

Polyester fibers for textiles and clothing

Conventional (or virgin) polyesters are strong, flexible, recyclable and durable materials that can be converted into synthetic fibers. Since polyesters usually do not absorb moisture, naturally resists stains and are consider a good insulator, polyesters are very popular within clothing, home furnishings, industrial fabrics, and electrical insulation sectors.

Due to the above-mentioned properties, polyesters have surpassed cotton as the most used fiber in textiles. Europe stands out as the world's largest importer of synthetic fibers (see Figure 4). Over 70 % of synthetic textile fibers are processed into clothing and household textiles. The remainder is used for technical textiles (e.g., safety wear) and industrial uses (e.g., vehicles and machinery) [12]. Synthetic fibers are cheap and versatile, enabling the production of cheap, fast fashion and high-performance textiles for durable clothing.

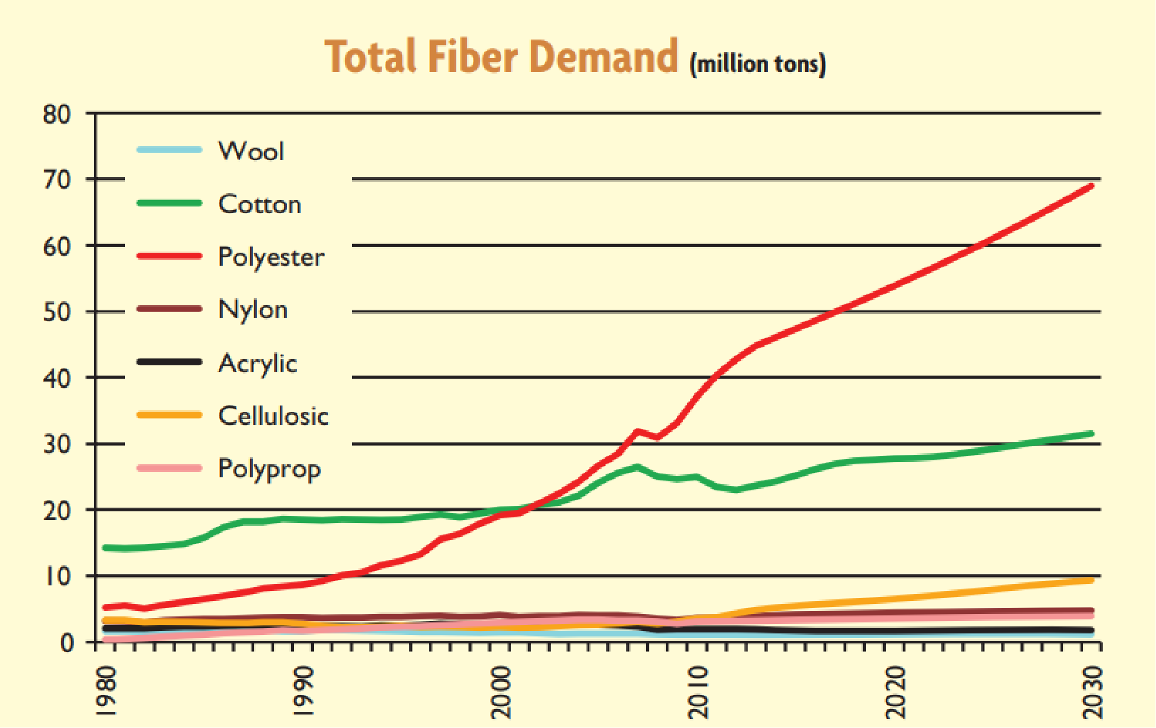


Figure 4: Textile fiber market demand trends. Reproduced from source: TextileWorld[13]

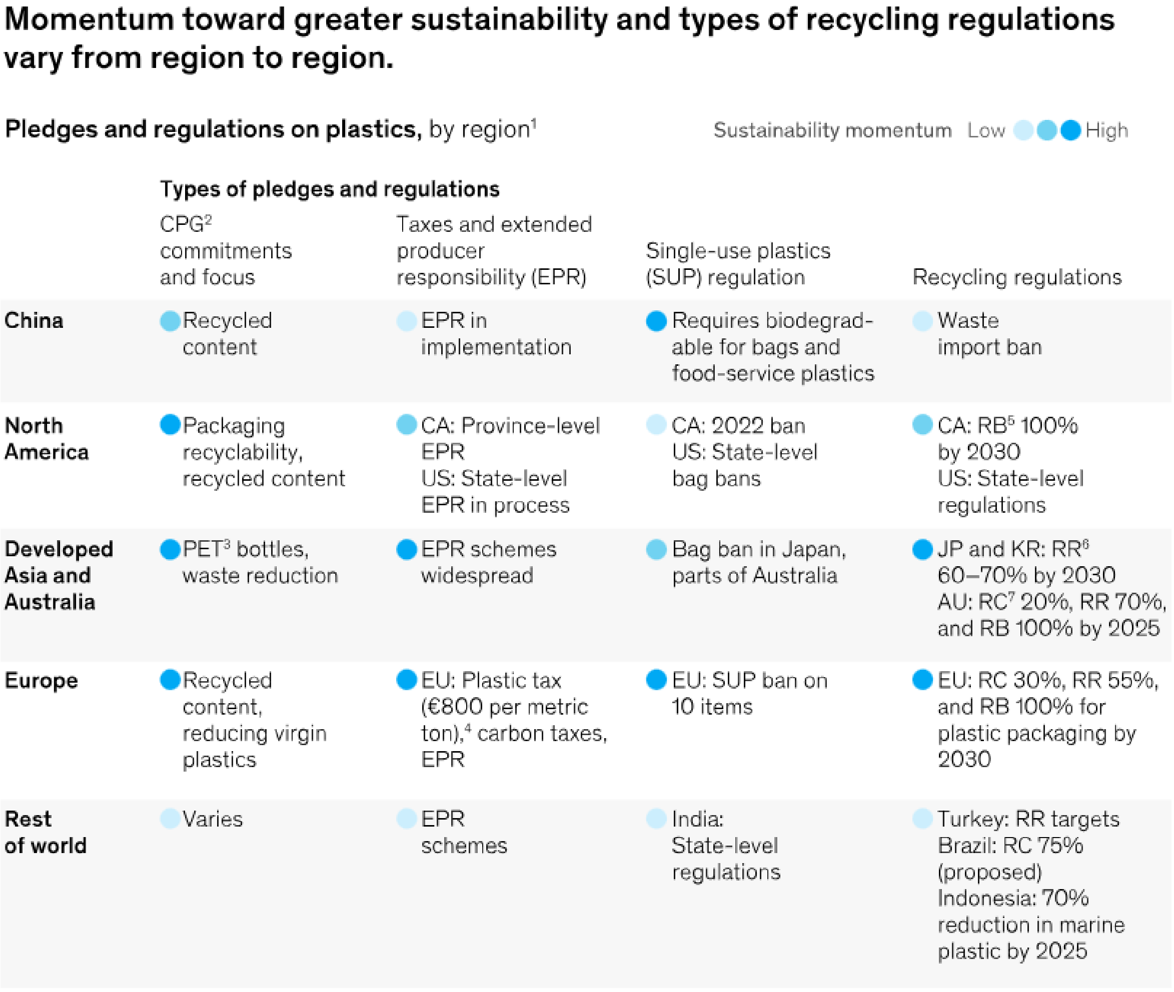
EU synthetic fibre production amounted to 2.24 million tonnes in 2018: 1.78 million tonnes were imported, 0.36 million tonnes exported, and 3.66 million tonnes consumed [14].

4.1.2. Regulatory framework and assessment

The previous section aimed at highlighting the relevance of polyesters and their properties over other different type of plastics, resulting in its preferent use in the most wide and transversal sectors globally: textiles, packaging and complex reinforced materials.

Its huge production rates and the fossil-based raw matters used for that can cause significant environmental issues if recycling or re-use routes are not deployed to decrease the production of virgin fossil-based materials. To decrease the waste volumes, as well as other aspects, the EU has a regulatory framework that applies and provides the basis for polyester fibers, and some of the recycling routes for these materials.

A clean overview is described in Figure 5 regarding the current state and penetration of European policy and regulatory frameworks for polyesters comprehended under plastic waste in comparison with several other nations and global regions. The following subsections will break down the different regulations and standards.



Momentum toward greater sustainability and types of recycling regulations vary from region to region.

Pledges and regulations on plastics, by region[1]

Sustainability momentum Low ○ ◐ ● High

Types of pledges and regulations

	CPG[2] commitments and focus	Taxes and extended producer responsibility (EPR)	Single-use plastics (SUP) regulation	Recycling regulations
China	◐ Recycled content	○ EPR in implementation	● Requires biodegradable for bags and food-service plastics	○ Waste import ban
North America	● Packaging recyclability, recycled content	◐ CA: Province-level EPR US: State-level EPR in process	○ CA: 2022 ban US: State-level bag bans	◐ CA: RB[5] 100% by 2030 US: State-level regulations
Developed Asia and Australia	● PET[3] bottles, waste reduction	● EPR schemes widespread	◐ Bag ban in Japan, parts of Australia	● JP and KR: RR[6] 60–70% by 2030 AU: RC[7] 20%, RR 70%, and RB 100% by 2025
Europe	● Recycled content, reducing virgin plastics	● EU: Plastic tax (€800 per metric ton),[4] carbon taxes, EPR	● EU: SUP ban on 10 items	● EU: RC 30%, RR 55%, and RB 100% for plastic packaging by 2030
Rest of world	○ Varies	○ EPR schemes	○ India: State-level regulations	○ Turkey: RR targets Brazil: RC 75% (proposed) Indonesia: 70% reduction in marine plastic by 2025

Figure 5: Increased consumer awareness, CPG pledges, and regulationsfor recycled polymers. Source: McKinsey & Company[15]

Plastics Strategy:

In January 2018, the European Commission adopted a new strategy for plastics in a circular economy, which aims to make all plastics recyclable by 2030 and reduce plastic waste in the environment. The strategy includes measures to reduce plastic consumption, increase recycling rates, and promote the development of a market for recycled plastics.[16]

Main Action pathways are clearly described under the following themes:

- Making recycling profitable for business
    - new rules on packaging to improve the recyclability of plastics and increase the demand for recycled plastic content.
    - improving the separate collection of plastic waste
    - launching an EU-wide pledging campaign targeting industry and public authorities
- Curbing plastic waste
    - a Directive on single use plastic products and fishing gear
    - measures to restrict the use of microplastics in products and address and reduce the unintentional release of microplastics into the environment.
    - measures on bio-based, biodegradable and compostable plastics
    - new rules on port reception facilities to tackle sea-based marine litter.
- Driving innovation and investment
    - scaling up support for innovation, with an additional €100 million to develop smarter and more recyclable plastics materials, to make recycling processes more efficient, and to trace and remove hazardous substances and contaminants from recycled plastics.
- Spurring global change
    - working with international partners to devise global solutions and develop international standards on plastics.

Packaging Waste Directive (94/62/EC)

This directive sets out requirements for packaging materials and packaging waste, including recycling targets and labeling requirements for packaging. It requires member states to establish recycling and recovery targets for packaging waste, including plastics. [17]

The Packaging Directive aims to

- harmonise national measures on packaging and the management of packaging waste.
- provide a high level of environmental protection.
- ensure the good functioning of the internal market.

The Directive also sets the following specific targets shown in Table 2 for recycling plastic packaging.

Table 2. Specific targets for recycling plastic packaging.

	Current targets	By 2025 (%)	By 2030 (%)
All packaging	55	65	70
Plastic	25	50	55
Wood	15	25	30
Ferrous Metals	50 (incl. Al)	70	80
Aluminium	-	50	60
Glass	60	70	75
Paper and cardboard	60	75	85

This Directive has been recently reviewed and amended to include:

- Modified Annex I by adding a list of illustrative examples of packaging.
- adding sustainable consumption reduction measures for plastic carrier bags in 2015
- setting additional waste prevention and reuse obligations for EU countries, and raising recycling targets on packaging waste
- providing for mandatory setting up of packaging Extended Producer Responsibility (EPR) schemes as part of the legislative proposals adopted under the circular economy package in 2018.

Related to the packaging sector, there is the Single-Use Plastics Directive (EU) 2019/904:

This directive aims to reduce marine litter and promote a circular economy for plastics by restricting the sale and use of certain single-use plastic products and introducing extended producer responsibility schemes for certain plastic products, including packaging. [18]

The objectives of this Directive are to prevent and reduce the impact of certain plastic products on the environment, in particular the aquatic environment, and on human health, as well as to promote the transition to a circular economy with innovative and sustainable business models, products and materials, thus also contributing to the efficient functioning of the internal market.

Some criteria and specifications are specially underlined for polyester based-products such as PET bottles in its Article 6.5.a about recycling rates:

“With regard to beverage bottles listed in Part F of the Annex, each Member State shall ensure that: from 2025, beverage bottles listed in Part F of the Annex which are manufactured from polyethylene terephthalate as the major component (‘PET bottles’) contain at least 25 % recycled plastic, calculated as an average for all PET bottles placed on the market on the territory of that Member State”

Textiles Strategy

In 2021, the European Commission launched a new strategy for sustainable textiles, which aims to promote a circular and sustainable textile industry in the EU. The strategy includes measures to increase the recycling and reuse of textiles, reduce the environmental impact of textile production, and promote sustainable textile design and business models.

The Strategy lays out a forward-looking set of actions. The Commission will:

- Set design requirements for textiles to make them last longer, easier to repair and recycle, as well as requirements on minimum recycled content.
- Introduce clearer information and a Digital Product Passport
- Reverse overproduction and overconsumption and discourage the destruction of unsold or returned textiles.
- Address the unintentional release of microplastics from synthetic textiles.
- Tackle greenwashing to empower consumers and raise awareness about sustainable fashion.
- Introduce mandatory and harmonised Extender Producer Responsibility rules for textiles in all Member States and incentivise producers to design products that are more sustainable.
- Restrict the export of textile waste and promote sustainable textiles globally.
- Incentivise circular business models, including reuse and repair sectors.
- Encourage companies and Member States to support the objectives of the Strategy.

To enhance the correct implementation of this actions to the European and outbound market, the path will be followed by these main steps:

  - Establishment of the proper framework to set eco-design requirements for products by the Eco-design for Sustainable Products Regulation
  - Tackle greenwashing
  - The "Reset the Trend" campaign (#ReFashionNow) was launched in 2023 to raise awareness about sustainable fashion.
  - The Waste Shipment Regulation, proposed in 2021, will help restrict the export of textile waste.
  - In 2023 the Commission proposed a revision to the Waste Framework Directive to introduce mandatory and harmonised Extended Producer Responsibility (EPR) schemes for textiles in all EU Member States.
  - Transition Pathway for the Textiles Ecosystem, published in 2023, and the European Circular Economy Stakeholder Platform (since 2018) promote and foster cooperation between industry, public authorities, social partners and other stakeholders.
- Other relevant specific sector regulations applied to polyesters.
  - Textile sector: *Regulation (EU) No 1007/2011* on textile fiber names and related labeling and marking of the fiber composition of textile products: This regulation requires textile products sold in the EU to indicate the fiber content on their labels, including the percentage of polyester used.
  - Packaging sector: *Regulation (EC) No 1935/2004* on materials and articles intended to come into contact with food: This regulation sets out specific requirements for materials, including polyester, that are used in contact with food.
  - Reinforced materials sector: *Directive 2014/90/EU* on marine equipment: This directive sets out requirements for marine equipment, including polyester materials used in boats and other watercraft.
  - Reinforced Materials: *Regulation (EU) No 305/2011* on construction products: This regulation sets out requirements for the performance of construction products, including polyester materials used in building and construction.
  - Across sectors: *Regulation (EU) 2019/1020* on market surveillance and compliance of products: This regulation requires member states to carry out market surveillance and enforce compliance with product safety regulations, including those related to polyester materials used in various sectors.
- Quality standards for the processing of polyester fibers and yarns and for textile manufacturing
  - EN 15381: This standard provides guidelines for the production of recycled textiles. It covers the entire recycling process, from the collection of textile waste to the production of new textile products.
  - EN 15797:2018 - Industrial washing and finishing of textile products: This standard specifies procedures for the industrial washing and finishing of textile products, including those made from polyester, and includes requirements for durability and safety.

Standards applied to polyester for manufacturing packaging

- ISO 18601:2013 - Packaging and the environment - General requirements for the use of ISO standards in the field of packaging and the environment: This standard provides guidelines for the use of ISO standards related to packaging and the environment, including standards for recycled materials.
- EN 13430:2014 - Packaging - Requirements for packaging recoverable through composting and biodegradation - Test scheme and evaluation criteria for the final acceptance of packaging: This standard specifies requirements and test methods for the compostability and biodegradability of packaging materials, including those made from recycled materials.

- ISO 15378:2017 - Primary packaging materials for medicinal products - Particular requirements for the application of ISO 9001:2015, with reference to good manufacturing practice (GMP): This standard specifies requirements for the quality management system for primary packaging materials for medicinal products, including those made from recycled materials.
- EN 13432:2000 - Packaging - Requirements for packaging recoverable through composting and biodegradation - Test scheme and evaluation criteria for the final acceptance of packaging: This standard specifies requirements and test methods for the compostability and biodegradability of packaging materials, including those made from recycled materials.
- ISO 18602:2013 - Packaging and the environment - Handling and storage of packaging and intermediate packaging for hygiene-sensitive products - Guidance: This standard provides guidelines for the handling and storage of packaging and intermediate packaging for hygiene-sensitive products, including those made from recycled materials.

By reviewing the regulations and applicable compliance framework, is considered that, as shown in Table 3, the secondary market based on polyester from packaging, textile fibres are in a good ongoing state of functioning from a purely regulatory perspective. Secondary markets based on complex composed polyester reinforced materials are yet under development and will ned further policy-making and stakeholders to stablish a more conclusive path for its growth.

Table 3. Polyester SRM market evaluation

Criteria	Result	Value
Non-policy-driven supply and demand	No. Packaging and textile strategies launched recycling and re-use targets to enhance prospective pathways for implementing wastes into secondary markets. However, few bonding regulatory requirements are established for textile fibres or complex composite reinforced polyester fibres, to increase the availability of recycled feedstock in novel products.	1
Included in compliance schemes for packaging waste or extended producer responsibility schemes	Producers may be required to meet specific recycling targets, promote eco-design, or contribute to recycling infrastructure development. The specifics of the schemes can vary significantly between countries. However, regarding EPR schemes targeting textiles waste were not as prevalent as packaging waste EPR programs. Some regions have started exploring and piloting textile EPR initiatives to address the environmental challenges associated with textile waste disposal and promote circularity in the textile industry.	2
Non-competition from energy use	PET bottles in Europe have an average collection rate of 60% and a recycling rate of 50%; levels of recycling for non-bottle PET applications are very low. However, new bottles only contain on average around 17% recycled PET. Incineration still represents one of the main operations for the recovery rates of packaging and textile	1
Product specifications are standardised	There are specific regulations and standards for the manufacturing and marketing of textiles and packaging containing recycled polyester fibres and/or PET materials. These regulations usually focus on aspects such as product composition, physical and chemical properties of the recycled material, and certification labels.	3
No regulatory barriers to using SRMs as inputs in manufacturing	In industries where PET is used for packaging food and beverages, there are often strict regulations concerning the safety and suitability of materials that come into contact with food. These regulations may impose specific requirements on recycled materials, including rPET, to ensure that they meet food contact safety standards.	1
Overall result	**Average Status**	**1.8**

4.2. Wood

4.2.1. Sector Overview

This section gives an overview of the wood sector, in particular the wood residues generated by the wood sector.

Forests in the Union extend over approximately 158 million hectares (2019), which represents about 5 % of the total area of forests in the world. Overall, forests cover about 37.7% of the Union's territory. The six Member States with the largest forest area (Sweden, Finland, Spain, France, Germany and Poland) account for about two thirds of the Union's forest area [19]. Moreover, at the national level, forest cover varies significantly: while more than 60% of the territory of Finland, Sweden and Slovenia is covered by forests, in the Netherlands this proportion is only 8.9%. On the other hand, unlike in many areas of the world where deforestation is a serious problem, the forest area in the Union is increasing between 1990 and 2010, it gained about 11 million hectares thanks to natural expansion and reforestation efforts.

Wood is a versatile raw material that can be used for various applications in the paper, packaging, furniture, housing and other sectors. In Europe, more than 50% of the mass of raw wood material harvested per year is used for energy in the first stage of processing by manufacturing industries [20]]. These processes produce products that become the raw material for further processing, as a result of which, further amounts of wood biomass are used for energy purposes. Below it is showed a summary of the amount of raw material consumed by the woodworking industries, according to the 2020 FAO Forest Products Report [21]:

Table 4. Wood goods consumed by the woodworking industries (2020) in Europe. Source: FAO Forest Products 2020 Report.

Material	Thousand tonnes/m3
Roundwood	780.546
Wood fuel	168.220
Industrial roundwood	612.326
Chips and particles	764.934
Wood pellets and other agglomerates	33.933
Wood residues	64.404
Sawnwood	114.416
Wood-based panels	78.881
Pulp and recovered paper	47.366
Paper and paperboard	86.090

Once wood materials are considered wood waste, they can be categorised depending to their quality and other aspects that the origin or hazardousness, following the European Residue List [22]. Depending on its quality, wood waste can be recycled, used as energy or disposed of in landfills. A large amount of wood waste is included in construction and demolition waste (CDW), which accounts for approximately 35% of all waste generated in the EU [23].

Some examples of catalogued wood residues are showed below:

- Group 03 "Wastes from wood processing and the production of panels and furniture, pulp, paper and cardboard". This category includes wastes from wood processing and the production of panels and furniture (bark, cork, sawdust, shavings, cuttings, etc.), wastes from wood preservation treatments and wastes from the production and processing of pulp, paper and cardboard.

- Group 15 "Packaging wastes, absorbents, wiping cloths, filter materials and protective clothing not otherwise specified". Wooden packaging is included in this category.
- Group 17 "Wood, glass and plastic". This category includes wood wastes (with and without hazardous substances).

Groups 19 and 20, which include some more generic wastes that are not included in other categories. According to the BIOREG project [24] (based on Eurostat data base), in 2016 54,76 million tons of wood waste were generated in EU countries, witch over 48 million of that was treated, which is 88%.

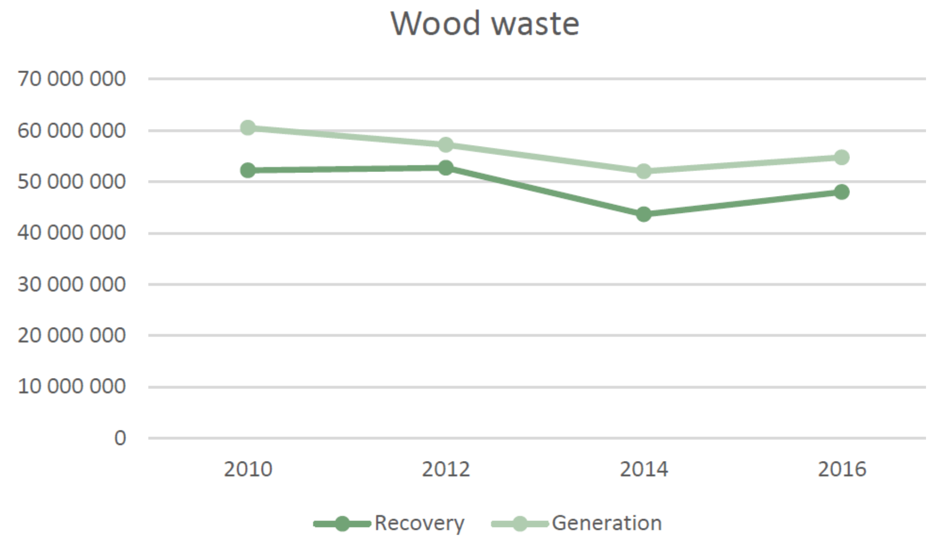


Figure 6. Wood waste generated in EU countries vs wood waste treated.

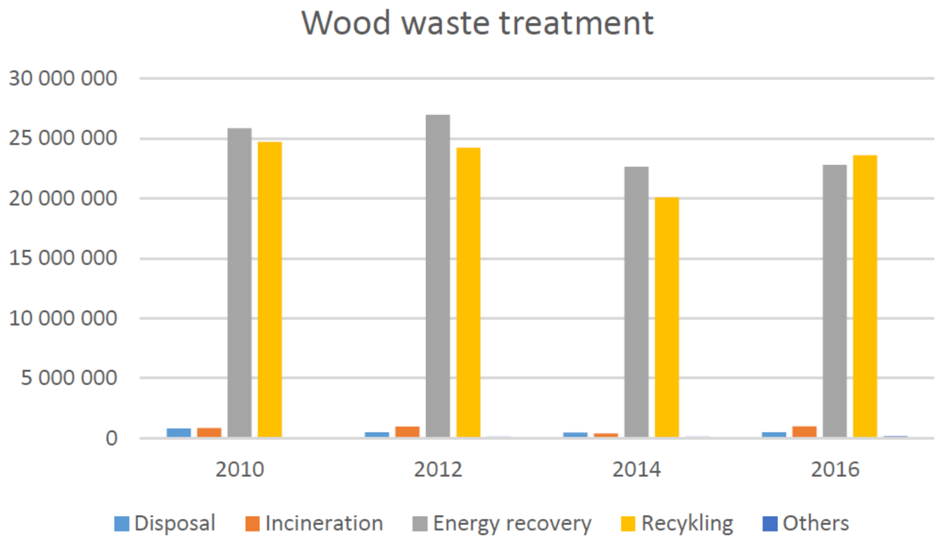


Figure 7. Wood waste treatment.

It can be observed that the level of wood waste disposal is low. However, there are wood residues that can be treated in different ways. It should be noted that not all wood waste is recovered yet. In addition, it should be noted that much wood waste is not collected or separated, and some is used in households inappropriately (combustion in domestic heating systems such as open fireplaces) or burned in the open air on demolition or construction sites. All of this represents unused wood waste potential and, due to lack of data, is difficult to fully characterize.

For wood raw material management to be efficient, it would be necessary to calculate how much of the collected wood remains in the manufactured products and how much becomes waste. In addition, it should also be taken into account that in many cases, this waste can become a valuable secondary raw material for other industries [20]].

Wood is a very versatile material, and its use and transformation also depends on the wood species, such as conifers, which have very diverse uses. As a result, wood has a key role to play in the implementation of effective measures in the global bioeconomy. In the new bioeconomy concept, sustainable management of wood and other organic resources is expected to take priority over other types of resource exploitation in order to ensure the availability of such raw materials and the sustainability of biomass [25].

In the long term, it is being assumed that forest wood will not be the only biomass source, but that post-production biomass obtained in the industry and post-consumer biomass and other less common sources will also have a relevant role in the value chain, favouring that all of them can be reintroduced in reuse and recycling cycles.

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Biomass, in addition to its use for the manufacture of products, can also be used as a source of energy generation, for example in production processes, as wood products can be directly treated as biofuels. On the other hand, wood residues can also be burned as fuel by individuals or organisations in low-power heating appliances.

In summary, wood residues can be a valuable secondary raw material for different industries and also for energy purposes. However, to ensure resource use, forest management and industry production processes must be efficient and involve all stakeholders in the value chain.

4.2.2. Regulatory framework and assessment

The EU Framework Directive on Waste provides a definition of waste as "...any substance or object which the holder discards or intends or is required to discard..."113. In the context of the wood waste industry, production residues are generally considered waste unless they are classified as by-products114. By-products, also known as non-waste production residues, are substances or objects that meet the criteria outlined in Article 5 of the Waste Framework Directive, which are as follows:

- The further use of the substance or object is certain.
- The substance or object can be used directly without any additional processing, other than normal industrial practices.
- The substance or object is generated as an integral part of a production process.

The further use of the substance or object is lawful, meaning it complies with all relevant product, environmental, and health protection requirements for its specific use and does not result in adverse environmental or human health impacts [In].

These criteria can be applied to excess material generated during a primary production process, which can be reused directly either within the same primary production process or in other integrated productions, as long as reuse is certain and does not require further processing (Other than being adapted to the appropriate size for being integrated into the final product). The Commission has the authority to establish specific criteria for substances or objects, such as wood, to be considered by-products rather than waste. However, as of now, no such criteria have been defined. Therefore, wood waste that meets the definition of waste must always be considered as waste unless specific legal provisions at the Member State level have introduced criteria for its classification as a by-product.

Wood waste can be used for different purposes in industry and in other contexts such as domestic energy consumption. The most significant and relevant waste policies and legislation that represent an impact on the management of wood wastes within the European framework are described below:

- Waste framework Directive (2008/98/CE) aims to encourage national waste prevention programs and promote recycling and recovery of waste. This Directive establishes the principles and rules for waste management in the European Union. It states that wood waste should be managed in accordance with the principles of the waste hierarchy, prioritising prevention, preparation for re-use, recycling and other forms of recovery over disposal.
- Directive 94/62/EC of 20 December 1994 on packaging and packaging waste.
- Related to the goals for wood wasted derived from packaging, EU rules on packaging and packaging waste cover both packaging design and packaging waste management. They aim to deal with the increasing quantities of packaging waste, which cause environmental problems. They also aim to remove barriers in the internal market – caused by EU countries adopting different rules on packaging design [26].
- The Packaging Directive aims to harmonise national measures on packaging and the management of packaging waste, prevent the production of packaging waste, and promote the reuse, recycling and other forms of recovering of packaging waste, instead of its final disposal. It establishes that, by end of 2024, EU countries should ensure that producer responsibility schemes are established for all packaging. The Directive also sets the following specific targets for recycling, modified by the Proposal for a Regulation of The European Parliament and of the Council on Packaging and Packaging Waste, amending Regulation (EU) 2019/1020 and Directive (EU) 2019/904, and repealing Directive 94/62/EC (pending approval): Specific targets for packaging waste (EU Parliament).

Table 5. Specific targets for packaging waste (EU Parliament).

	Current targets (%)	By 2025 (%)	By 2030 (%)
All packaging	55	65	70
Plastic	25	50	55
Wood	15	25	30
Ferrous metals	50 (incl. Al)	70	80
Aluminium	-	50	60
Glass	60	70	75
Paper and cardboard	60	75	85

- Directive (EU) 2018/852 of the European Parliament and of the Council of 30 May 2018 amending Directive 94/62/EC on packaging and packaging waste.
- It sets recycling and recovery targets, as well as management requirements for producers and extended producer responsibility schemes, including wood products.
- Regulation (Eu) No 305/2011 of the European Parliament and of the Council of 9 March 2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC.
- It establishes safety, performance and sustainability requirements for wood and wood-based products used in construction.

- Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC.
- The REACH Regulation regulates the production, import and use of chemicals in the European Union. It affects wood products treated with chemicals, as it establishes requirements for the registration, evaluation and authorisation of these substances.
- Regulation (EU) No 995/2010 of the European Parliament and of the Council of 20 October 2010 laying down the obligations of operators who place timber and timber products on the market.

This regulation stablishes the rules for the marketing of timber and timber products in construction, as well as the requirements for the certification of the sustainability of timber.

- Commission Decision of 18 December 2014 amending Decision 2000/532/EC on the list of waste pursuant to Directive 2008/98/EC of the European Parliament and of the Council – “The List of Wastes and Hazardous Wastes” legislate and define the use of wood waste and defines categories or generic types of hazardous waste that are relevant to wood waste.
- Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste.
- Directive 2009/28 / EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources. The Directive creates a common framework for the use of renewable energies in the EU to reduce greenhouse gas emissions and promote cleaner transport. To this end, it sets targets for all EU countries with the overall ambition of achieving a 20% share of energy from renewable sources in EU energy and a share of 10% of this type of energy in transport by 2020.
- This legislation could affect to wood waste in the case of the secondary raw materials obtained from the wood extraction and treatment, were used as fuel for heat energy.

Once the main legislations and policies have been studied, the secondary market based on waste wood is suitable for the wood waste to reuse the different materials obtained in wood industries and avoid generating new residues. In this vein, below it is showed a table with an assessment of the potential market of wood waste according to the methodology proposed in the European Environmental Agency to the Secondary Raw Materials [27].

Table 6. Wood waste SRM market evaluation [27]

Criterion	Result	Value
Non-policy-driven supply and demand	No. The waste directives (WFD and PPWD) set requirements for separate collection and targets for recycling of wooden waste, which increases the availability of feedstock for recycling.	1
Included in compliance schemes for packaging waste or extended producer responsibility schemes	Yes. For wooden packing waste, most Member States have EPR schemes in place covering packaging (which will become mandatory by 2024).	3
No competition from energy use	No. Energy recovery competes strongly with recycling.	1
Product specifications are standardised	No. A standard for Solid Recovered Fuel (SRF) use has been developed, but that is not relevant to the SRM market.	1
No regulatory barriers to using SRMs as inputs in manufacturing	Yes. However, no EU-wide EoW criteria for wood exist.	3
Overall result	**Average status**	**1.8**

Value	Result
0-1	Not well-functioning
1-2	Average status
2-3	Well-functioning

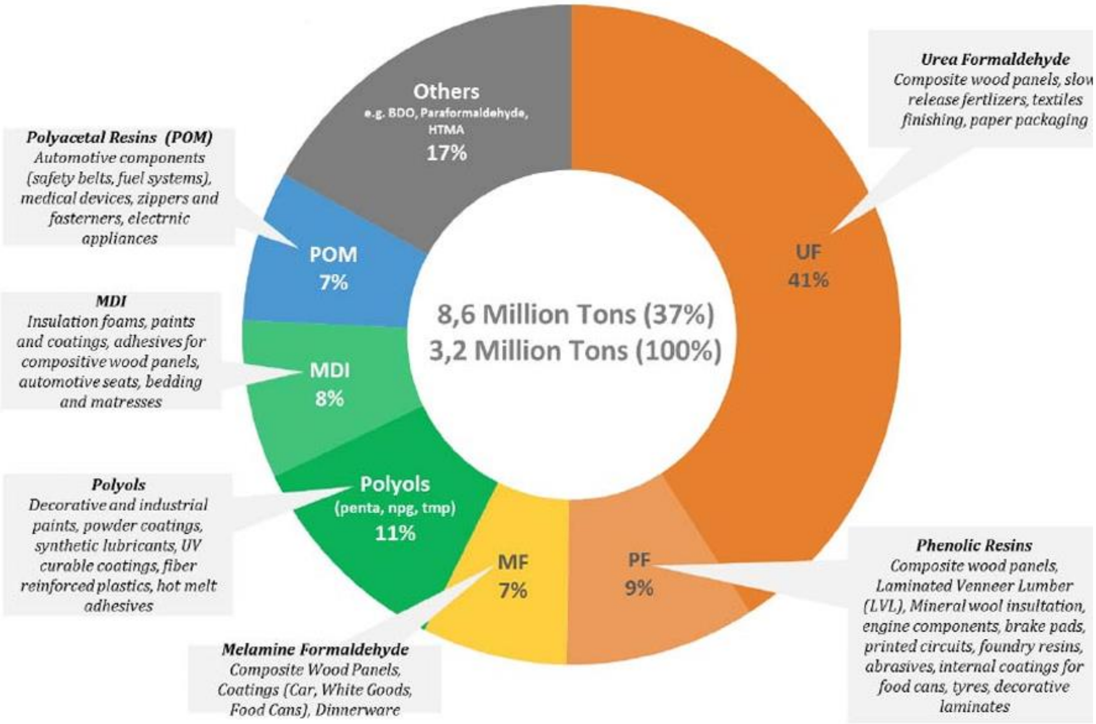
4.3. Resins

4.3.1. Sector Overview

Resins are typically viscous polymers that can be converted into rigid thermoset materials through a curing process triggered mainly by temperature, pressure and UV-light. Chemically speaking, resins can be comprised of various structures, such as polyesters (see section 4.1.1.), polycarbonates, acrylic, epoxy, among others. These materials are heavily used in a wide range of applications such as electronics, consumer goods and construction. In the construction sector, resins are an essential part of the manufacture of wood panels, which are sheets made from wood-based materials bonded together by an adhesive (a resin) that is then cured by means of heat and pressure. Accordingly, the woodworking sector is the world's largest user of adhesives, with 70% of the world's volume being used in said products [28]. Due to such large market share, and as the demonstrator assessed in the DigInTrace project targets the production of wood-based panels, the resins of interest for this report are the formaldehyde-based ones, as they dominate the market of resins used in wood panels.

The most common wood panel products are plywood, oriented strand board (OSB), particleboard, and fibreboard, which can either be structural and non-structural. Structural panels are created to withstand forces and serve specific purposes in structural systems such as buildings, houses, shipping containers, and unit load platforms. On the other hand, non-structural panels are manufactured for furniture, doors, and flooring, where factors other than strength and stiffness are essential. Most wood panel products have the benefit of valorising side streams, such as leftover chips, shavings, particles, and fibres. Figures point that more than 50% of the raw material in the wood-based panels industry is recycled or an industrial by-product, which is very positive from a sustainability point of view [29]. Furthermore, wood panels use relatively little energy to produce and may be comprised of sustainably produced raw materials under some certification schemes, e.g., the FSC (Forest Stewardship Council, a scheme that ensures that forests were responsibly managed). The demand for such materials has been increasing, as quality logs for traditional solid wood products become increasingly scarce and as technology evolves to deliver new attributes and applications for wood-based panels. Accordingly, these products have become specialized and are used widely, including as a substitute for metals and plastics in some applications. Resins are an important component, comprising typically 3-20 wt% depending on the type of product (e.g., plywood, fiberboard, particleboard), manufacturing process and final use. Higher-grade products, such as those used for structural applications, may have a higher resin content to ensure greater strength and durability. On the other hand, lower-grade panels intended for decorative or interior purposes may have a lower resin content. The lifespan of wood panels varies substantially depending on the quality and application (5-35 years).

As aforementioned, the majority of the resins used in wood-based panels are formaldehyde-based, i.e., urea-formaldehyde (UF), phenol-formaldehyde (PF), and melamine-formaldehyde (MF), see Figure 8 for figures from the EU. UF dominates the sector due to its low price and good properties, and the vast majority of UF resins (ca. 95%) is used in wood-based panels in EU [30]. PF resins are relatively more expensive and preferred for exterior grade panels, but also largely used in the sector. The EU region is also considered to be self-sufficient in terms of formaldehyde production (less than 1% is imported) [30]. The global formaldehyde market size was valued at USD 7.8 billion in 2020 and is expected to expand at a compound annual growth rate (CAGR) of 5.7% from 2021 to 2028 [31]. The building & construction end-use segment (covered mainly by resins) dominates the market, with a revenue share of over 30% in 2020. The predicted growth is based on the expansion of the construction sector and diversification in the possible applications for formaldehyde-resins (e.g., in textiles). On the other hand, a primary factor hindering market growth is the pronounced toxicity of formaldehyde. This have led to limitations in its applications, particularly in the personal care and cosmetics industry. In this context, there is also a growing trend of increasing restrictions on the use of formaldehyde in the resins sector, as well as a general pressure for the development of more sustainable resins (see section 4.3.2.).



Urea Formaldehyde
Composite wood panels, slow release fertlizers, textiles finishing, paper packaging

Polyacetal Resins (POM)
Automotive components (safety belts, fuel systems), medical devices, zippers and fasterners, electrnic appliances

MDI
Insulation foams, paints and coatings, adhesives for compositive wood panels, automotive seats, bedding and matresses

Polyols
Decorative and industrial paints, powder coatings, synthetic lubricants, UV curable coatings, fiber reinforced plastics, hot melt adhesives

Melamine Formaldehyde
Composite Wood Panels, Coatings (Car, White Goods, Food Cans), Dinnerware

Phenolic Resins
Composite wood panels, Laminated Venneer Lumber (LVL), Mineral wool insultation, engine components, brake pads, printed circuits, foundry resins, abrasives, internal coatings for food cans, tyres, decorative laminates

Figure 8. Main uses of formaldehyde and formaldehyde-derived products (2015). *Note: 3.2 million tonnes as 100% pure formaldehyde, 8.6 million tonnes as a 37% water solution (formalin) [30]

According to the latest statistics of resins production in EU (PRODCOM [32] data from 2021), a total of 5.2 million tons of urea-based, phenol-based and melamine-based resins were produced in 2021 (3.3 million tons[1], 0.9 million tons[2] and 1.0 million tons[3], respectively). Considering these large production numbers and wide range of uses, substantial amounts of materials containing resins are therefore disposed, and end of life possibilities are not yet fully exploited (see Section 5.3). The resins (adhesives) needed for the manufacture of wood panels constitute a concern in terms of sustainability: while versatile, cheap, well established and with great mechanical properties and water, chemical, and thermal resistance, they tend to be *i)* fully petro-based, with a production process that involves toxic compounds; *ii)* known to release formaldehyde over time, which is toxic to humans and the environment; *iii)* non-biodegradable in natural conditions; *iv)* not easily recyclable due to the irreversibly crosslinked structure; *v)* polluting when landfilled or incinerated.

For these reasons, changes in the sector are being proposed to:

- Encourage the development of new types of resins (e.g., formaldehyde-free, using biobased building blocks as a replacement to petro-based ones, recyclable). Currently, it is estimated that <10% of the total adhesive production in the EU is biobased [33]
- Encourage the development of reuse and recycling (mechanical and chemical) schemes.

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[1] Product code : 20165550
[2] Product code : 20165650
[3] Product code : 20165570

- Discourage the use of chemicals of concern in the resin's formulations (particularly formaldehyde)
- Prevent the landfilling/incineration of items containing said resins.
- Prevent the use of said resins in particular items (e.g., children's toys)

The following session will address the current regulatory framework related to the resins sector, with a focus on formaldehyde resins due to their extensive use in wood-based panels. Then, the five main criteria established by the EEA will be applied to the sector for an assessment and comparison with the other three sectors addressed in this report. Finally, section 5.3. will look into the recycling, upcycling, and reuse opportunities for resins, as well as the secondary markets of highest potential for implementation and main actors.

4.3.2. Regulatory framework and assessment

The EU has put increasing efforts on normative that push for the responsible management of wastes, valorization of wastes and overall byproducts, and the development of circular value chains that avoid pollution and environmental impacts, particularly greenhouse gas emissions. Notably, the EU Green Deal is a package of policy initiatives which target climate neutrality by 2050 (with a reduction of at least 55% of net emissions by 2030). While not always directly related, the specific directives described below might impact the developments within the resins sector. Important to mention, a directive is not applicable in the EU as a regulation – it is incorporated in the national legislation of the member states within a timeframe. A regulation has a binding legal force across the EU from the moment it is issued. To this date, there is no specific EU directive addressing wood-related resins (adhesives). For instance, adhesives are exempt from regulation under the Plastics Directive (2002/72/EC), being only covered by the Framework Regulation for food contact materials (1935/2004), which is not the case of the specific resins used in the production of wood panels.

Waste Framework Directive (2008/98/EC) and Amending Directive (EU) 2018/851

The so-called EU waste management law (Directive 2008/98/EC, also known as Waste Framework Directive [34]) had to be transposed into national laws by the end of 2010. This directive discloses basic waste management principles to protect human health and the environment. Furthermore, it explains when waste ceases to be waste and becomes a secondary raw material, and how to distinguish between waste and by-products. The Directive also introduces the "polluter pays principle" and the "extended producer responsibility". The foundation of EU waste management is the five-step waste hierarchy, which defines the preference for managing waste, going from Prevention (no-waste production) to Reuse, Recycling, Recovery and Disposal (see Figure 9). Accordingly, preventing waste is the preferred option, and sending waste to landfill should be the last resort.

Figure 9. Waste hierarchy as defined by the EU waste framework directive (D2008/98/EC)

An amendment to the Waste Framework Directive (WFD) was released in 2018 (2018/851 [34,35], to be transposed into national law by 2020), as part of a package of measures related to circular economy. Besides setting minimum operating requirements for extended producer-responsibility schemes, this directive strengthens rules on waste prevention and generation. On the latter, the main points that can be related to the resins sector (and wood wastes containing said resins) are:

- Support sustainable production and consumption models.
- Encourage the design, manufacturing and use of products that are resource efficient, durable, reparable, reusable and capable of being upgraded.
- Encourage the availability of spare parts, instruction manuals, technical information, or other means enabling the repair and re-use of products without compromising their quality and safety.
- Promote the reduction of the content of hazardous substances in materials and products.

The amendment sets new municipal-waste-recycling targets: by 2025, at least 55 wt% of municipal waste will have to be recycled, rising to 60 wt% by 2030 and 65 wt% by 2035. Furthermore, EU member states must establish collection and separation schemes for textiles and hazardous waste generated by households by 2025, as well as ensure that, by the end of 2023, all bio-waste is collected separately or recycled at source (e.g., by composting). In terms of construction and demolition waste (C&D), where wood panels could fit, the Waste Framework Directive sets a 2020 target of 70 wt% for the reuse, recycling and other types of material recovery. Importantly, except for a few countries, only about 50% of C&D waste is currently being recycled in EU [36]. A prevalent challenge is the lack of trust and standardization practices to guarantee the quality of recycled C&D materials. Moreover, there is uncertainty surrounding potential health risks for workers involved in using said materials. This scenario significantly diminishes the demand for C&D recycled materials, thereby slowing the progress of C&D waste management and the establishment of dedicated recycling infrastructures.

Within the WFD, it is important to address the topic of “hazardous waste”, which are wastes that pose a greater risk to the environment and human health due to their chemical or physical properties, e.g., toxicity and bioaccumulation, therefore requiring a stricter control and handling. Some resins, particularly those containing heavy metals or volatile organic compounds (VOCs), can be considered hazardous waste if they meet specific criteria. In detail, formaldehyde resins themselves are not classified as hazardous waste under the current EU regulations solely based on their chemical composition, as the formaldehyde release is considered to be within safe limits. Nonetheless, if waste materials containing resins contain substances that are classified as hazardous, they may be considered hazardous waste. This is the case of wood impregnated with certain preservatives, such as chromated copper arsenate (CCA), creosote and organohalogens (e.g., pentachlorophenol), substances that have been severely limited or banned nowadays but are still present in some older structural pieces such as wooden railway sleepers [37]. In the current regulatory framework, most wood panels and their resins are not considered hazardous waste.

Landfill of Waste Directive (1999/31/EC) and Amending Directive (EU) 2018/850

The landfill of waste directive [38] had to be transposed into national laws by 2001, being subsequently amended and transposed into law by 2020. This directive introduced technical requirements aiming to prevent, or reduce as much as possible, negative impacts from landfilling. Landfill sites were divided into three categories (for hazardous, non-hazardous, and inert wastes), where acceptance criteria that landfills must meet were set to ensure the proper handling and disposal of waste. These criteria aim to protect human health and the environment by specifying limits for various parameters, including waste composition, hazardous substances, and leachate and gas emissions.

The amending directive: *i)* introduces further restrictions on landfilling of all waste that is suitable for recycling or other material or energy recovery (from 2030); *ii)* limits the share of municipal waste landfilled to 10% or less (weight basis, by 2035); *iii)* introduces rules on calculating the attainment of municipal waste targets; *iv)* requires EU countries to put in place an effective quality control and traceability system for municipal waste landfilled; and *v)* allows EU countries to use economic instruments and other measures to encourage the application of the waste hierarchy introduced under

WFD (see Figure 9). The EU commission shall review the 10% target by the end of 2024 to either maintain or further reduce it. Further restrictions to the landfilling of non-hazardous waste other than municipal solid waste (MSW) are also envisioned in the near future. This could directly affect C&D wastes, as these are not considered MSW (only wood from furniture and small durable goods are considered MSW, whereas wood waste is the second-largest component of C&D debris after concrete).

Industrial Emissions Directive (2010/75/EU)

The Industrial Emissions Directive (IED) [39] sets out rules and regulations to minimize the negative environmental impact of industrial activities. The directive aims to achieve a high level of protection for the environment and human health by regulating the emissions and pollution generated by various industrial sectors. The IED establishes legally binding emission limit values for certain pollutants, including sulfur dioxide, nitrogen oxides, particulate matter, heavy metals, volatile organic compounds, and other hazardous substances. These limits aim to ensure that industrial emissions are minimized and do not exceed set thresholds. Furthermore, it requires the use of best available techniques (BAT) for various pollutants resulting from combustion processes.

The IED primarily addresses wood waste within the context of waste incineration for energy recovery, and resins present in wood waste are not specifically targeted. Nonetheless, the BAT Reference Document for the Production of Wood-based Panels [40] specifies the existing concerns on formaldehyde release, both during the production of wood panels (drying and pressing steps) and in finished panels, where UF resins release more formaldehyde than PF resins. Approaches for controlling said emissions involve *i)* selecting resins free from formaldehyde (e.g., polymeric methylene diphenyl diisocyanate, p-MDI), *ii)* using formaldehyde scavengers in the resin mix and *iii)* secondary abatement techniques such as scrubbers. Importantly, while formaldehyde-free, p-MDI is a petro-based option with its own toxicity issues and with a significantly higher cost compared to formaldehyde resins. It is also not compatible with medium density fiberboard (MDF) and particle board (PB) production processes, and more additives (waxes as release agents) are needed, which might lead to higher organic carbon associated emissions.

Eco-design Directive (2009/125/EC) and Framework on the Requirements for the Eco-design of Sustainable Products

The EU recently proposed an Eco-design for Sustainable Products Regulation with the objective of enhancing the durability, reusability, repairability, recyclability, and energy efficiency of consumer products, aligning with the goals of the Circular Economy Action plan [41]. This framework aims to replace the previous Eco-design Directive (2009/125/EC), which currently covers only energy-related products. In more detail, the new regulation covers most products (only a few sectors, such as food, feed, and medicinal products, are exempted), including energy-related products, e.g., appliances, heating and cooling equipment, electronic and electrical equipment, machinery, and other products with significant environmental impacts. It establishes specific requirements for these, focusing on key environmental aspects such as energy efficiency, material efficiency, water consumption, emissions, and waste generation. These requirements will be set through a comprehensive analysis of the product's life cycle, considering the entire supply chain, use phase, and end-of-life considerations, as well as the development of harmonized standards that support the implementation of the requirements. Some important points are highlighted below:

- The regulation should allow, under certain conditions, for the restriction, primarily for reasons other than chemical or food safety, of substances present in products or used in their manufacturing processes which negatively affect products' sustainability. This expands the scope of building blocks that might be discouraged or discontinued due to their high environmental impacts, being therefore applicable to components of resins formulations - including and beyond the ones focused on this study.
- The regulation should allow for the setting of requirements related to the tracking and communication of sustainability information, including the presence of substances of concern in products throughout their life cycle, including with a view to their decontamination and

recovery when they become waste. A clear communication of hazards and end of life strategies is likely to push current stakeholders towards products that score positively.

- To drive consumers towards more sustainable choices, labels should, when required by the delegated acts adopted pursuant to this Regulation, provide information allowing for the effective comparison of products, for instance by indicating classes of performance. A clear communication of sustainable metrics and benchmarking is likely to promote the development of more sustainable value chains in all addressed sectors.

Overall, an increased investment in the design, production & after-sales services of more sustainable products is expected, leading to a higher market share for them. This regulation proposal aims at boosting the economic value of the recycling, repair and re-use sectors while also increasing the number of products covered by sustainability requirements and decreasing non-compliance via proper communication/labelling and the setting of a digital product passport. The latter aspect is expected to largely impact consumer behaviour, as better product choices can be made when clear, accessible information is provided. While none of the abovementioned information specified products, resins nor chemicals, the eco-design concept will have an impact on the established value chains of many sectors (which are often linear and not designed having sustainability in mind).

Construction Products Regulation (EU) No 305/2011

Under the Construction Products Regulation (CPR), there are provisions that indirectly address the use of resins and the control of formaldehyde emissions in construction products, such as:

- Essential Requirements: The CPR sets out essential requirements that construction products must meet to be placed on the market. These requirements include mechanical resistance and stability, fire safety, hygiene, health, and the protection of the environment. While formaldehyde emissions are not explicitly mentioned, the regulation indirectly addresses the control of emissions that could arise from certain construction products, such as those using resins that may release formaldehyde.
- Harmonized Standards: The CPR facilitates the development of harmonized European standards (EN standards) that define technical specifications and assessment methods for construction products. The specific EN standards used in the wood panel industry are described in detail in section 3.3.2.7. and include specific requirements related to the emissions of harmful substances, including formaldehyde, from relevant construction products.
- CE Marking: Under the CPR, construction products that fall within the scope of a harmonized standard must undergo an assessment of their conformity with the essential requirements. Once the conformity assessment is completed, products can be affixed with the CE marking, indicating compliance with the applicable requirements. The assessment may consider factors related to emissions, including formaldehyde, when applicable standards exist.

A revision of the CPR was recently proposed (March 2022) [42], encompassing regulations for more environmentally friendly and safer construction products, along with enhanced digital product information for citizens, businesses, and other stakeholders. Consequently, several of the proposed options involve the adoption of a digital framework that aligns with the digital product passport.

Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH) Regulation (EC) No 1907/2006

The objective of REACH regulation is to ensure a high level of protection of human health and the environment through the registration, evaluation, authorization, and restriction of chemicals. REACH includes restrictions on formaldehyde, phenols, and derived resins. Some key points regarding said restrictions are listed below:

- Formaldehyde is classified as a hazardous substance under REACH due to its toxic and carcinogenic properties. Its classification is based on its potential to cause adverse health effects, particularly through inhalation and skin contact.

- Formaldehyde resins, such as those used in various products and materials, may be subject to restrictions on their formaldehyde emissions. The specific restrictions can vary depending on the product and its intended use. For instance, certain composite wood products, including plywood, particleboard, and medium-density fiberboard (MDF), are subject to formaldehyde emission limits under REACH.
- Some phenols (e.g., 4-nonylphenol, 2-methoxyphenol, 2-phenylphenol, bisphenol A diglycidyl ether) are identified as substances of very high concern (SVHC) due to their hazardous properties, such as carcinogenicity, mutagenicity, or reproductive toxicity, and may be subject to authorization or restrictions under REACH. SVHCs are included in the Candidate List and may undergo further evaluation and regulatory action. Regarding the typical building blocks of resins, phenol (CAS number 108-95-2) and urea (CAS number 57-13-6) are not included in the SVHC list, but formaldehyde (CAS number 50-00-0) and melamine (CAS number 108-78-1) are.
- The REACH Regulation includes specific restrictions on the manufacturing, placing on the market, and use of certain phenols due to their hazardous properties. These restrictions can include concentration limits, usage bans, or specific conditions for use to ensure the safe handling and minimize the risks associated with these substances.
- Manufacturers, importers, and downstream users of resins are responsible for complying with the restrictions outlined under REACH. Regulatory authorities monitor compliance and enforcement to ensure that resins on the market meet the specified requirements.
- The restriction process under REACH involves a comprehensive assessment of the risks associated with the substance or group of substances. If formaldehyde (or other) resins are determined to pose unacceptable risks to human health or the environment, restrictions can be imposed to limit or control their use, concentration, or release.

In 2018, The EU commission has issued a draft legislation to restrict formaldehyde and formaldehyde releasers in mixtures and articles for consumer uses [43]. The new law would be implemented in two phases, starting 36 months after the date of entry into force (potentially 2026). The objective is to impose limitations on the sale or utilization of articles that emit formaldehyde at concentrations equal to or exceeding 0.124 mg/m3 in the air of a test chamber, as per the specifications outlined in EN 717-1. Formaldehyde released by an article can originate from the formaldehyde itself or other substances employed as formaldehyde releasers during the manufacturing process.

Within the EU, voluntary agreements have already been established to proactively restrict formaldehyde emissions originating from wood-based products. Accordingly, manufacturers of wood panels have adopted an industry agreement, committing to produce panels that conform to the formaldehyde emission class E1 as defined by the harmonized European Standard EN 13986 (concentration threshold of 0.124 mg/m3 in the air of a test chamber following the European Standard EN 717-1). While this is also endorsed by the European furniture industry, the absence of a legally binding Union-wide measure might lead to non-compliant articles being introduced into the EU market. This is the main reason for the proposal for a restriction of formaldehyde releasers that don’t comply with said standards.

Other interesting initiatives such as the EU Ecolabel, introduced by Regulation (EC) No 66/2010 of the European Parliament [44] and of the Council and the EU green public procurement (GPP) criteria [45] are broader in scope but have a reduced impact so far due to the limitations of voluntary approaches. In detail, the GPP criteria for furniture include requirements related to the use of sustainable materials, avoidance or reduction of hazardous substances, and adherence to strict emission standards. These criteria aim to promote the use of environmentally preferable materials and products, which may indirectly encourage the selection of furniture with low formaldehyde emissions and a reduced reliance on fossil-based molecules. Furthermore, the GPP criteria often emphasize the use of materials from sustainable sources, the reduction of greenhouse gas emissions, and the promotion of circular economy principles. By focusing on these aspects, the GPP aims to encourage the procurement of products with lower environmental impacts.

EN standards

Wood panels must adhere to EN standards, which include requirements on the physical characteristics of the panel (e.g., bending strength, stability, load bearings and swelling properties), and their classification according to the amount of free formaldehyde in the finished board. For indoor and furniture applications, a lower formaldehyde content is required (E1 emission class). Formaldehyde emission classes in finished panels, defined in Annex B of EN 13986, are as follows:

- Class E1: ≤ 8 mg/100g dry board or <0.124 mg/m3 according to EN 717-1
- Class E2: > 8 to < 30mg/100g dry board or >0.124– < 0.3 mg/m3 according to EN 717-1

In addition to EN standards, the manufacturing of panels is experiencing a growing impact from product emission quality standards enforced beyond Europe, notably the CARB standards derived from legislation in California. These standards play a significant role in regulating the emission levels of panels used in furniture applications, with limit values set considerably lower than the minimum emission standard specified in the EN standards. For example, the formaldehyde emission classes outlined in ATCM 93120, which is a part of CARB standards, are as follows:

- CARB emission limit for MDF: 0.11 ppm
- CARB emission limit for particleboard: 0.09 ppm

To have a global reach, numerous producers within the EU-27 region are manufacturing panels with low formaldehyde emissions to comply with CARB standards. This is possible by using resins that do not contain formaldehyde. Another strategy to limit the quantity of free formaldehyde in the end product is to use a well-balanced ratio of formaldehyde to urea in the resin. This balance is achieved by incorporating additional urea, increasing the amount of hardening agent, and adjusting the press time and temperature during the manufacturing process. Ongoing research aims to identify substitutes for formaldehyde in resins, with particular attention given to isocyanate resins, primarily p-MDI, already used in the production of OSB, flex board, and rigid boards. However, the potential of this resin is significantly hindered by limited global production capacity, which falls short of meeting the demand from the wood-based panels industry, as well as higher costs. Furthermore, the adoption of p-MDI means significant changes in wood-resin blending, mat forming, and press operations, which can be costly for manufacturers. Finally, safety concerns also exist for p-MDI, as it can be toxic if not handled properly. Exposure to p-MDI can cause respiratory and skin irritation, allergic reactions, and sensitization in some individuals. Prolonged or repeated exposure can lead to more severe health effects, including asthma, lung damage, and occupational asthma.

Several standards exist to specify the properties of wood-based panels for the various categories of panel products based on their intended use in interior, exterior, humid, and load-bearing applications. The following standards serve as examples where the resin has a high impact. Examples related to resins beyond the construction sector are also listed.

- EN 15383 – Construction products - Emission classes for the evaluation of VOC emissions
- EN 16516 – Construction products - Assessment of release of dangerous substances - Determination of emissions into indoor air
- EN 204 – Classification of thermoplastic wood adhesives for non-structural applications
- EN 205 – Classification of thermosetting wood adhesives for non-structural applications
- EN 302 – Adhesives - Test methods for wood adhesives for non-structural applications
- EN 15493 – Adhesives - Wood-to-wood adhesive bonds - Test methods and requirements
- EN 17178 – Resilient floor coverings - Determination of peel resistance of the bonding
- EN 13986 – Wood-based panels for use in construction - Characteristics, evaluation of conformity, and marking.

- EN 15185 – Resilient, textile, and laminate floor coverings - Essential characteristics - Residual indentation and vertical deformation
- EN 301 – Adhesives - Wood adhesives for non-structural applications - Test methods
- EN 15425 – Adhesives - Determination of free formaldehyde content
- EN 12004 – Adhesives for tiles - Requirements, evaluation of conformity, classification, and designation
- EN 717-1 – Wood-based panels. Determination of formaldehyde release. Formaldehyde emission by the chamber method

Circular Bioeconomy in the European regulatory context

The EU has been taking important actions towards the establishment of a circular bioeconomy. Accordingly, the European Green Deal [46], European Union's new growth strategy, has set the EU on a course to become a sustainable climate neutral and circular economy by 2050. The circular economy action plan [47] emphasises the importance of finding nature-friendly biobased solutions and points to the launch of a new *Strategy for a Sustainable Built Environment* that will promote circularity principles throughout the lifecycle of buildings by:

- Addressing the sustainability performance of construction products, including the possible introduction of recycled content requirements for certain products (considering their safety and functionality).
- Promoting measures to improve the durability and adaptability of built assets in line with the circular economy principles and developing digital logbooks for buildings.
- Integrating life cycle assessments in public procurement and the EU sustainable finance framework, as well as exploring carbon reduction targets and the potential of carbon storage.
- Considering a revision of material recovery targets set in EU legislation for construction and demolition waste and its material-specific fractions.
- Promoting initiatives to reduce soil sealing, rehabilitate abandoned or contaminated brownfields and increase the safe, sustainable, and circular use of excavated soils.

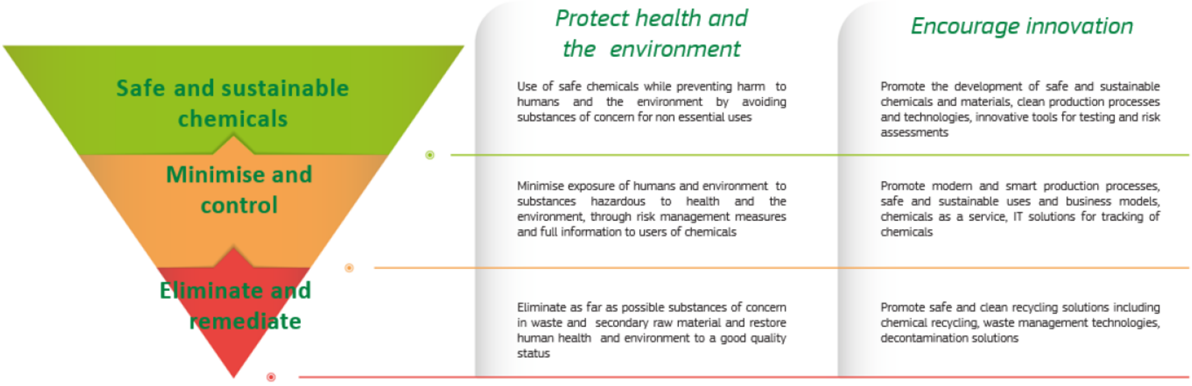
The *Sustainable Carbon Cycles* action [48] outlines a visionary goal where a minimum of 20% sustainably sourced non-fossil carbon is used in chemical and plastic products. However, further scientific developments are needed to incorporate the assessment of biogenic carbon uptake and release throughout the lifecycle of these products. Ongoing discussions within the framework of the *UN Life Cycle Initiative* [49]. It is important to note that only biobased products with extended lifespans, which are not incinerated upon reaching the end of their useful life, can effectively contribute to beneficial carbon storage effects. This is a clear opportunity for the development of long-lasting, biobased resins that can contribute positively to the establishment of a European circular bioeconomy and the avoidance of GHG emissions.

Finally, the recent EU Communication *Chemicals Strategy for Sustainability Towards a Toxic-Free Environment* [50] outlines the vision and strategy for achieving a toxic-free and sustainable environment with regards to chemicals. A summary of key points covered in the communication are:

- Hazardous Chemicals. The EU recognizes that certain hazardous chemicals pose significant risks to human health and the environment. It aims to accelerate the identification and substitution of the most harmful substances, including endocrine disruptors (typically phenols, such as BPA), persistent organic pollutants (POPs), and chemicals of emerging concern.
- Safe and Sustainable Chemicals. The EU aims to promote the use of safe and sustainable chemicals throughout their life cycle. This involves encouraging the development and adoption of safer alternatives, promoting innovation in green chemistry, and supporting the substitution of hazardous substances with safer, sustainable-by-design options.

- Risk Assessment and Management: The strategy emphasizes the importance of robust and transparent risk assessment and management processes for chemicals. It aims to enhance the use of science-based methodologies, improve data availability, and ensure better coordination between regulatory frameworks, such as REACH, CLP, and Biocidal Products Regulation.
- Circular Economy. The communication highlights the importance of transitioning to a circular economy model for chemicals. It promotes the reduction of hazardous substances in products, the use of recycled and renewable materials, and the adoption of sustainable production and consumption patterns.
- International Cooperation. The EU intends to strengthen international cooperation on chemicals management, harmonize approaches, and promote the adoption of high standards and best practices globally. This includes engagement with international partners, such as the United Nations, to address global challenges related to chemicals.
- Enforcement and Governance. The communication emphasizes the need for effective enforcement of chemical regulations and the enhancement of governance and regulatory coherence within the EU. It aims to strengthen enforcement capacity, ensure access to information, and improve transparency and accountability.

This roadmap will guide the EU's actions and initiatives to achieve a more sustainable and safe chemicals management system, promoting the transition to a toxic-free environment and supporting a sustainable and competitive European chemical industry (see Figure 10). Future developments following this roadmap will surely impact the resins sector, which is heavily fossil-based and include products currently difficult to recycle and/or repurpose.



	Protect health and the environment	Encourage innovation
Safe and sustainable chemicals	Use of safe chemicals while preventing harm to humans and the environment by avoiding substances of concern for non essential uses	Promote the development of safe and sustainable chemicals and materials, clean production processes and technologies, innovative tools for testing and risk assessments
Minimise and control	Minimise exposure of humans and environment to substances hazardous to health and the environment, through risk management measures and full information to users of chemicals	Promote modern and smart production processes, safe and sustainable uses and business models, chemicals as a service, IT solutions for tracking of chemicals
Eliminate and remediate	Eliminate as far as possible substances of concern in waste and secondary raw material and restore human health and environment to a good quality status	Promote safe and clean recycling solutions including chemical recycling, waste management technologies, decontamination solutions

Figure 10. The proposed new hierarchy in chemicals management [50]

As seen along this section, the resins sector is very diverse and reliant on fossil-based building blocks such as phenols, aromatics, and formaldehyde. This report focused on resins used for wood-panels, an application that absorbs >50% of the global production and where formaldehyde-based resins largely dominate (particularly UF, PF and MF resins). It can be observed that said resins are well standardized in terms of properties (being an industrial value chain, EN standards exist for most applications where resins are used, e.g., wood panels and composites), with safety aspects addressed by the REACH regulation. In this context, some common components of resins, notably formaldehyde, are tightly regulated to avoid harmful emissions and human exposure. Formaldehyde is part of the SVHC (substances of very high concern) list within REACH, and it is expected that the current movement for a safer and more sustainable chemistry in EU will incentivize the development of alternatives for the sector.

Another aspect is that the end of life is not addressed by any specific regulation targeting resins, as the current directives target rather end products that contain resins (in varying proportions and chemistries). Traditional resins are difficult to recycle, since during the curing step, irreversible bonds are created in the polymer, and it cannot be re-melted. Furthermore, end products tend to be multimaterial, where a resin matrix involves ("glues") other components such as wood, carbon fibres, layers of other plastics, metals, textiles, etc. This further complicates the recycling schemes and while some possibilities are being explored (see section 5.3), further research is needed to fully close the loop. It is expected that the major EU efforts to avoid emissions and support waste valorisation schemes will lead to the development of circular value chains, the avoidance of landfilling and decrease in the usage of said materials for energy recovery.

Finally, by evaluating the resin sector's strengths and weaknesses, the related secondary raw material (SRM) market is in a low-to-average status of functioning from a purely regulatory perspective (see table below).

Table 7. Wood Resins SRM market evaluation [27]

Criteria	Result	Value
Non-policy-driven supply and demand	Partially: regulations support recycling of end products that contain resins (e.g., wood panels used in construction), but recycling schemes for resins are not fully developed and no specific regulation exist for resins. Also, virgin resins tend to be cheap, e.g., UF. Thus, the market needs policies to push the demand and develop secondary raw material value chains.	2
Included in compliance schemes for packaging waste or extended producer responsibility schemes	No: most resins are not involved in closed-loop circular schemes and the end of life involves landfilling and energy recovery.	1
Non-competition from energy use	No: energy recovery competes strongly with recycling due to the difficulties related to the isolation and viable recycling of resins.	1
Product specifications are standardised	Yes: resins are largely used as a component in materials, such as construction (wood panels) and technical pieces (wind blades, airplane parts, etc). Various EN standards (e.g., EN 13986) and regulations (e.g., Construction Products Regulation, CPR) exists for said applications.	3
No regulatory barriers to using SRMs as inputs in manufacturing	No: traditional resins rely on building blocks in which safety is a concern (e.g., formaldehyde, BPA, melamine). This brings issues for final applications (e.g., tightening of regulations, a clear example being formaldehyde emissions from resins), but also for reprocessing and reintroducing said materials into the market. Furthermore, end products containing resins are usually multimaterial and difficult to sort, separate and recycle in a feasible manner.	1
Overall result	**Average Status**	**1.6**

4.4. WEEE Plastics

4.4.1. Sector Overview

As has been done in the previous sections, this section analyses the plastics sector, specifically plastics from Waste Electrical and Electronic Equipment (WEEE).

Whether in the form of household appliances, computers, mobile phones or any other type, Electrical and electronic equipment (EEE) has become an essential part of modern societies, and this has led to a considerable increase in its production. In the EU alone, the amount of electrical and electronic equipment placed on the market increased from 7.6 million tonnes in 2012 to a total of 12.4 million tonnes in 2020 [51]. In addition, several characteristics are associated with these products, such as short lifetimes, rapid changes in technologies and limited repair options for reuse [52,53].

All this leads to an increase in the volumes of WEEE generated. Globally, the volumes generated increased from 41.8 Mt in 2014 to 53.6 Mt in 2019, and with a projected annual growth rate of 2 Mt, volumes could reach 74.7 Mt by 2030 [52]. Importantly, WEEE do not come only from municipal waste collecting, but also commercial/industrial sources. These usually have a different classification and collecting flows. The overall quantities reported officially are a sum of all aforementioned flows of WEEE.

All WEEE, or most of it, consists mainly of ferrous and non-ferrous metals, glass and plastics, the latter representing approximately 30% of the total WEEE volume by weight generated per year [54].

As shown in Figure 11, plastics from WEEE are varied and their quantity differs depending on the product in question.

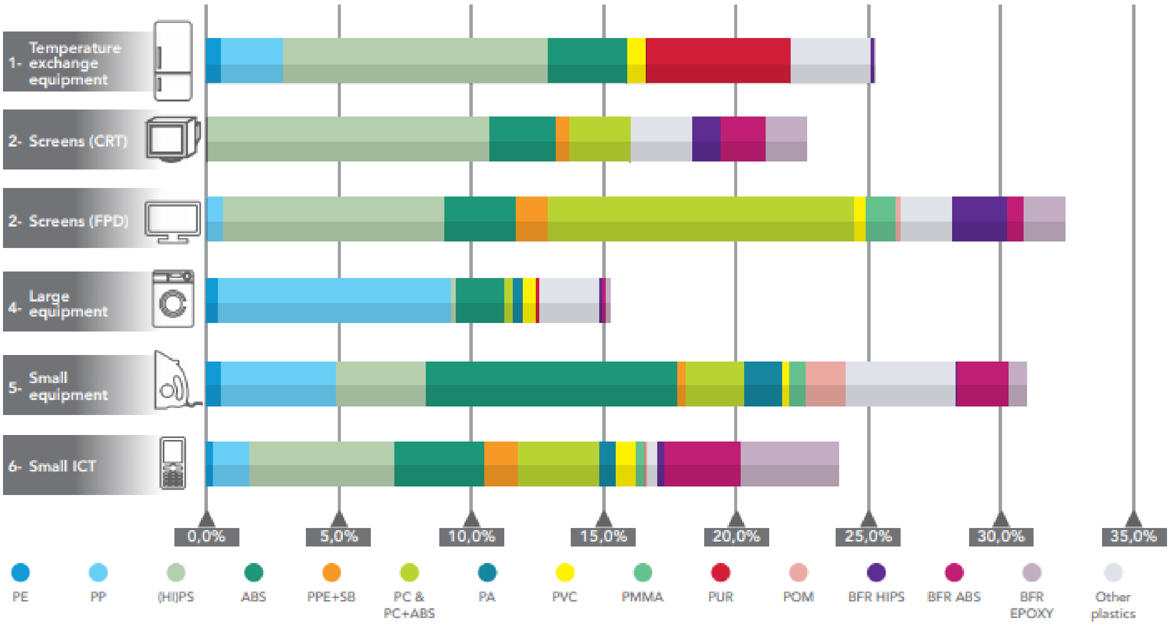


Figure 11. Composition of WEEEP, according to different products [55]

In any case, the most used plastics, as shown in the figure below, are acrylonitrile butadiene styrene (ABS), polypropylene (PP), high impact polystyrene (HIPS), other polymers and polycarbonate (PC)/ABS blends [53,55], accounting for more than the 75% of all WEEE plastics (WEEEP) [55–57].

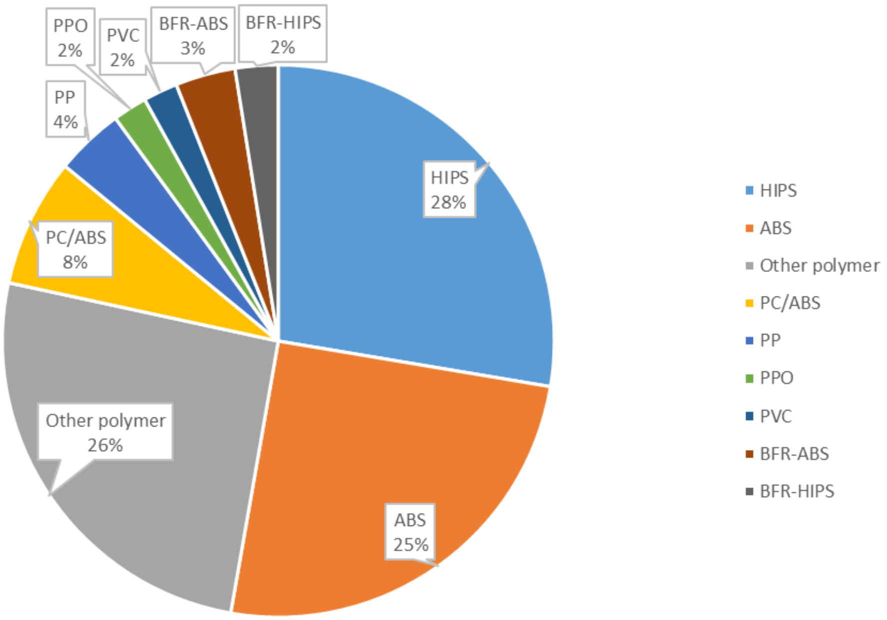


Figure 12. Main types of plastic used in EEE [56,57]

This mix of plastics, low collection rates, with a European average of 35%, and the limited capacity of technology for proper sorting are some of the main reasons why only very little of these plastics are recycled (30 – 50% of collected plastics) [53,55,58]. The other main challenge that the recycling of WEEEP faces is the presence of hazardous components, like flame retardants (halogenated compounds with chlorinated and brominated FRs) and potentially some toxic elements (i.e., lead, cadmium, mercury) [53,55]. In addition, flame retardants are commonly used in combination with antimony trioxide ($Sb2O3$), as a synergy with Sb consumption for this use accounting for about half of its total production [59,60].

In summary, waste electrical and electronic equipment (WEEE) has the dual characteristic of containing both hazardous substances and valuable recoverable materials, which is why, as discussed in the following section, various regulatory measures have been taken to regulate its use and disposal and it is an interesting material with which to create a secondary market.

4.4.2. Regulatory framework and assessment

As discussed in the previous section, WEEE are waste from a wide variety of products that are rapidly increasing in production and are characterised by a complex mixture of materials, some of which are hazardous. WEEE can cause significant environmental and health problems if the discarded equipment is not properly managed [61]. Furthermore, with effective management of modern electronics, resources that are rare and expensive can be recycled/reused [61]. To cope with this increase in waste volume, as well as other aspects, the EU has a regulatory framework consisting mainly of the WEEE Directive and the RoHS Directive [61]. However, this framework is characterised by its prioritisation of the protection of the environment and human health, which has led to several strict guidelines affecting the recycling of electronic plastics. An example of this are the continuous alterations of threshold limits for substances in products and waste [62].

The WEEE Directive

The Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment, popularly known as the WEEE Directive, seeks to contribute to sustainable development through measures to protect the environment and human health by preventing or reducing the adverse impacts of the generation and management of waste electrical and electronic equipment (WEEE) and by reducing the overall impacts of resource use and improving resource efficiency [63].

From its articles, the WEEE directive imposes on member countries the obligation to:

- Encourage cooperation between producers and recyclers to design electrical equipment which can be reused, dismantled, or recovered in line with the eco-design directive (Directive 2009/125/EC).
- Minimise the disposal of WEEE in unsorted municipal waste.
- Allow private households and distributors to return WEEE free of charge.
- Ban the disposal of WEEE collected separately that has not been properly treated.
- Ensure a minimum annual WEEE collection rate. From 2016, this is 45% of total weight of electrical and electronic equipment that was sold in the past 3 years and, from 2019, this target increases to 65% which is equivalent to a target for collection of 85% of the total WEEE generated.
- Check all plants treating WEEE are officially licensed.
- Establish a register of all companies producing or importing electrical and electronic equipment.
- Carry out inspections to ensure compliance with the legislation and establish penalties for breaking the law.

At the same time, it requires producers to:

- Meet minimum treatment targets for different WEEE categories, notably: small and large household appliances; IT and telecommunications equipment; consumer equipment and photovoltaic panels; lighting equipment; electrical and electronic tools (except for large-scale stationary industrial tools); toys, leisure and sports equipment; medical devices (with the exception of all implanted and infected products); monitoring and control instruments; automatic dispensers (Annex I).
- Depending on the aforementioned categories, recovery rates shall rise progressively from 70-80% (2012-2015) to 75-85% (from 2015 onwards), as described in Annex V.
- Depending on the aforementioned categories, reuse and recycling rates shall rise progressively from 50-75% (2012-2015) to 55-80% (from 2015 onwards), as described in Annex V.
- Finance the cost of collection, treatment, recovery, and environmentally sound disposal from all users, apart from private households, of products on sale from 13 August 2005.
- Provide information to the public on how WEEE can be returned and collected.

If emphasis is placed on the point that all separately collected WEEE shall undergo treatment, which shall include as a minimum the removal of all fluids and a selective treatment separating the WEEE from a number of substances, mixtures and components listed in Annex VII of the Directive itself.

The list includes the above-mentioned plastics containing brominated flame retardants, which together with the presence of other potential toxic substances made the recycling of WEEE difficult.

Brominated flame retardants (BFRs) have long been used as additives or reactive FRs since the 1980s in the manufacture of EEE [64], and although their application has been considerably reduced since 2009, they are still found in WEEE in non-negligible concentrations [53].

In any case, the two main reasons for their currently low recycling rates are the mixing of different polymers and the presence of additives, such as flame retardants [53]. This is made more problematic by the WEEE Directive's lack of a methodology for how these materials should be treated after collection or indications specifying the substances and/or thresholds for defining whether plastics are considered to contain BFRs or not [55].

The RoHS Directive

As a second way to address the growing volume of WEEE, as well as the potential environmental contamination that may be caused by BFRs (especially PBDEs) from discarded or recycled WEEE,

DIRECTIVE 2011/65/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment, also known as the RoHS Directive was introduced [61,65].

The RoHS Directive aims to prevent risks to human health and the environment related to the management of electronic and electrical waste [65].

In other words, since 1 July 2006, new EEE placed on the market may not contain the following substances and may not exceed the maximum tolerable concentrations by weight indicated below [66]:

- Lead (0,1 %)
- Mercury (0,1 %)
- Cadmium (0,01 %)
- Hexavalent chromium (0,1 %)
- Polybrominated biphenyls (PBB) (0,1 %)
- Polybrominated diphenyl ethers (PBDE) (0,1 %)
- Bis(2-ethylhexyl) phthalate (DEHP) (0,1 %)
- Butyl benzyl phthalate (BBP) (0,1 %)
- Dibutyl phthalate (DBP) (0,1 %)
- Diisobutyl phthalate (DIBP) (0,1 %)

Other relevant parts of the regulatory framework

- The POPs Regulation

While the RoHS Directive restricts the use of certain hazardous substances in electrical and electronic equipment, Directive 2019/1021/EU (POPs Regulation) sets concentration limits for POPs in waste.

In other words, the POPs regulation states that in cases where his limits are exceeded, the materials may not be disposed of by conventional means, such as landfill or recycling, but must be treated by methods that ensure their destruction (e.g., incineration for energy recovery). However, if these wastes containing POPs are treated in such a way that the hazardous substances are separated from the article, then it is allowed to dispose of these articles by conventional means.

- REACH Regulation

The Regulation on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) aims to protect human health and the environment from the harmful effects of chemicals. It seeks to ensure that all substances and products are manufactured and used safely and to promote good communication between all actors in the supply chain [67,68].

Within this regulation it is stated that:

  - Each company handling more than 1 tonne of chemicals per year must register with the European Chemicals Agency (ECHA). To do so, they must, for both substances and mixtures, identify the risks associated with the management of these substances [67,68].
  - A number of substances will be limited and if necessary banned, if they pose an unacceptable risk to health or the environment [67,68].

As a consequence of the application of regulations such as REACH or RoHS and strategies like the circular economy and the context of the WEEE plastics recycling sector itself, it has experienced certain complications in carrying out its activity, among which are the following:

  - The lack of information about the specific composition of the plastic waste arriving at the recycling facility [69].
  - The content of recycled plastics introduces a risk of unknown contaminants [70].

  - The obligation to identify restricted substances when they reach the end of their useful life, together with the difficulty of generating useful data on them, as it is not economically viable to measure all restricted substances during the recycling process [70,71].
  - A ban on the re-use of some of the recovered substances in EEE, as well as, although possible, the recycling of plastics as they contain some types of FRs [71].
- European List of Wastes (LoW)

The Regulation (EC) 2150/2002 on waste statistics obliges the Member States to report statistical data on waste generation and waste treatment according to the statistical waste nomenclature EWC-Stat. The European List of Wastes (LoW) is the waste classification in the EU for administrative purposes, i.e. for permitting and supervision in the field of waste generation and management. The LoW defines 839 waste types which are structured into 20 chapters, mainly according to the source of the waste (i.e. the economic sector or process of origin). In the LoW, there are two chapters explicitly referring to WEEE: chapter 16 "*wastes not otherwise specified in the list*" and chapter 20 "*municipal wastes (household waste and similar commercial, industrial and institutional wastes) including separately collected fractions*". Due to the complexity of WEEE in terms of composition and hazardous components, several subclassifications exist (see Figure below).

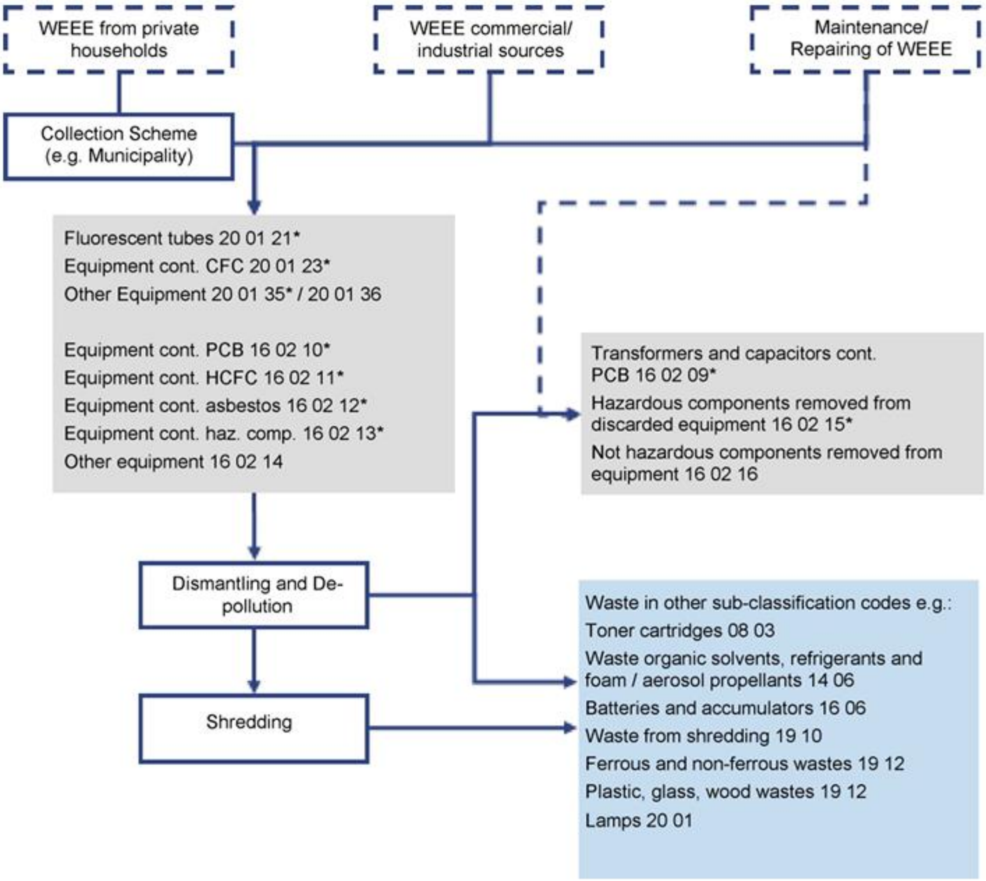


Figure 13. LoW entries from WEEE treatment

Quality standards for the processing of WEEE

Following the entry into force of the WEEE Directive, the EC commissioned CENELEC to develop the current CENELEC 50625 series, which sets out the regulatory requirements for the collection, transport, and treatment of WEEE in accordance with the Directive, and EN 50614 that covers the preparing for re-use of WEEE arising from electrical and electronic equipment [72]. The WEEELABEX system is based on both standards, which is why such certification can guarantee that its holder treats WEEE in accordance with the EU standard [72].

The EN 50625 series includes 5 European Standards (EN) and 6 Technical Specifications (TS) [55]. These standards are legally binding for WEEE treatment facilities in Belgium, Ireland, France, Lithuania, and the Netherlands, while in others, such as Switzerland, compliance with EN 50625 is part of the contractual obligations of WEEE treatment operators towards producer responsibility organisations (PROs) [55]. In addition, since 2019, European representatives of EEE producers, WEEE collection systems and WEEE recyclers are calling for mandatory EU-wide implementation of the EN 50625 series of standards [73].

Regarding plastics, the EN 50625 series of standards requires the separation of plastics containing BFRs for plastic fractions resulting from the treatment of displays (WEEE category 2) and small appliances (categories 5 and 6). For this purpose, it introduces a separation threshold of 2,000 ppm Br. Those fractions with > 2,000 ppm Br are considered to contain BFRs, while those below are considered not to contain BFRs. However, as a consequence of the comparison between the BFR levels in unsorted WEEEP from 2010 and 2015/2017, it has been observed that the total Br level corresponding to the LPCL for PBDE is now considerably higher than a decade ago. This reduction in the share of PBDEs in the total Br content of WEEEP makes the statistical considerations that were the basis for setting the 2000 ppm threshold in the CEN WEEE standards probably obsolete [55].

To sum up, EU laws restrict the use of certain hazardous substances in electrical and electronic equipment through the RoHS Directive, while the WEEE Directive promotes the collection and recycling of such equipment. In addition, there is a set of standards, EN 50625, which, in line with the WEEE Directive, sets out the regulatory requirements for the collection, transport and treatment of WEEE.

However, there are some gaps or difficulties, such as the fact that the WEEE Directive does not specify the treatment of flame retardants, which is one of the main reasons why higher recycling rates are not achieved, nor the substances and thresholds for defining whether plastics are considered to contain BFRs or not.

It is true that Directives such as RoHS and POPs define limits on the concentrations of BFRs accepted in products and waste respectively, while the EN 50625 standards do so for Br.

However, in the POPs regulation plastics recycling is not a permitted treatment method for waste containing POPs above the low POP content, while the EN 50625 standards are probably outdated meaning that high percentages of the plastic volumes arriving at recycling facilities cannot be effectively recycled.

Finally, it is important to mention that EU countries adopt the EU directive and classification in different ways. As an example, in Italy (demo case of the DigInTrace project targeting WEEE), the subclassification is defined by the CDRAEE (*Centro di Coordinamento RAEE*), a coordinating consortium comprised of 13 EEE producers, created to respect the Italian lex DL 14/03/2014 n.49 Art. 33/34, which is based in the WEEE directive. The CDRAEE defines the following six WEEE categories:

- R1: Temperature exchange equipment (e.g. fridges, freezers, radiators, etc)
- R2: Screens, monitors and equipment with screens having a surface area greater than 100 cm^2
- R3: Lighting equipment (e.g. LED lamps, fluorescent lamps, etc)
- R4: Large equipment (e.g. washing machines, dishwashers, photovoltaic panels, etc)
- R5: Small equipment (e.g. vacuum cleaners, kitchen appliances, etc)
- R6: Small IT and telecommunications equipment (with no external dimension exceeding 50 cm)

The Italian demo of DigInTrace will focus on the WEEE from categories R1, R2 and R4.

With all this in mind, and considering its strengths and weaknesses, it is considered that, as shown in the table below, the secondary market based on plastics from WEEE is in a good state of functioning from a purely regulatory perspective.

Table 8. WEEE SRM market evaluation [27]

Criteria	Result	Value
Non-policy-driven supply and demand	The WEEE Directive includes several targets of collection, which are not being met [74]. It is unlikely that the market can survive economically without such policies that drive demand and/or supply.	1
Included in compliance schemes for packaging waste or extended producer responsibility schemes	The WEEE Directive extends producer responsibility by introducing minimum treatment targets for the different categories of WEEE, financial obligations for the cost of collection, treatment, recovery, and environmentally sound disposal for all users, as well as providing information to the public on how WEEE can be returned and collected	3
Non-competition from energy use	It is estimated that currently 44% of recovered plastics are recycled for energy recovery or fuel replacement in cement kilns [75]. At the same time, it is predicted that by 2050 recycling will increase to 50%, while energy recovery alone will account for 44% [52].	2
Product specifications are standardised	The EN 50625 series of standards sets requirements for the collection, transport and treatment of WEEE in compliance with the WEEE Directive, which are legally binding for WEEE treatment facilities in some countries of the EU	3
No regulatory barriers to using SRMs as inputs in manufacturing	Large percentages of plastic volumes are not being recycled because of the limits set by the RoHS and POPs Directives, as well as those of the EN 50625 standards, as it is required the irreversible destruction of the BFRs contained in the material, processes that are still under development. This leaves companies with no alternative but to incinerate the plastic.	1
Overall result	**Average Status**	**2**

5. Analysis of the suitability of waste streams to be converted into secondary materials

In this section, an initial analysis is carried out, for each waste stream, of the characteristics of the current collection, management and treatment systems, with the aim of obtaining:

- Recycling/Reuse and upcycling opportunities, where ideas can be extracted on new solutions and technologies that enable the reuse and recycling of each waste stream, so as to favour its reintroduction into the value chain and a positive impact on it.
- Potential pathways and main actors, where potential exploitation and commercialisation pathways linked to the secondary raw materials of each waste stream are identified, showing in which sectors and through which stakeholders the materials under study can be reintroduced into the value chain.

Along this section, different opportunities that promote reusability/recycling (where materials or products can be used again to prevent waste and reduce the demand for natural resources) and upcycling (transformation of discarded materials or products into objects of higher value or quality, giving them a new useful life and diverting them from landfills) will be gathered for each of the studied materials management systems. Subsequently, the identification of the main actors that comprise the system and their current situation within it, along with potential avenues for improvement based on these opportunities, will be presented.

5.1. Polyesters

Currently, there are more than twenty types of plastics available, with the majority being developed and synthesized from petrochemical sources. These plastics exhibit variations in their degradability. While different plastics may have distinct structures, they can share similar covalent chemical bonds that connect their building blocks. Figure 14 provides examples of various plastics with similar chemical bonds, despite their structural differences. The prevalent covalent bonds in plastics include ester bonds, urethane bonds, and carbon-carbon bonds. Additionally, the level of crystallinity in plastics is another crucial factor that influences their biodegradability.

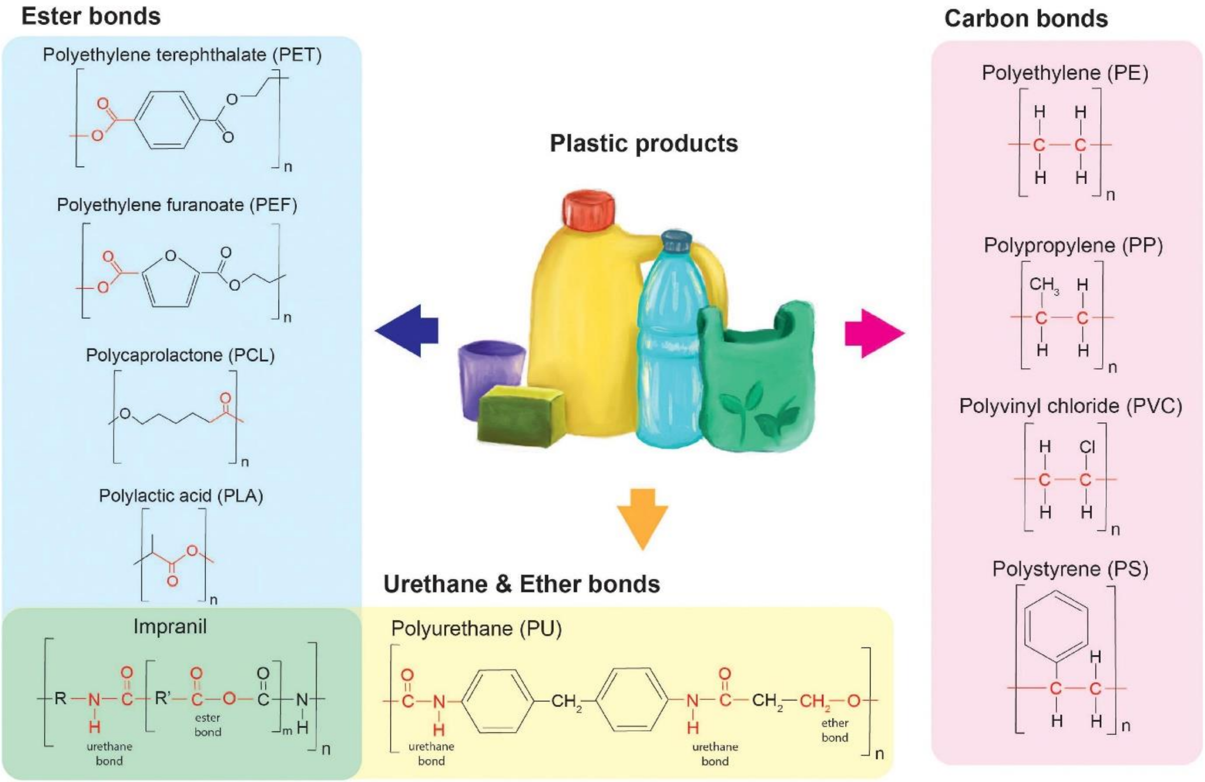


Figure 14. Plastics and their specific chemical bonds [76]

Polyester, a category of synthetic polymers, is formed by linking multiple chemical repeating units through ester (CO-O) groups. This group of materials offers a diverse range of properties, making it widely applicable in various practical uses. Among the many products that incorporate polyester are permanent-press fabrics, disposable soft-drink bottles, compact discs, rubber tires, and enamel paints. However, its applications extend beyond everyday items, finding significance in the biomedical field as well.

In the medical realm, polyester plays a crucial role due to its synthetic biodegradable nature, making it a highly sought-after choice for regenerative implantation surgeries, therapeutic cell culturing, and tissue repair [77]. The biocompatibility and biodegradability of polyesters enable their use in the manufacturing of medical devices like sutures, plates, bone fixation devices, stents, screws, and tissue repair materials. The physicochemical attributes of polyesters further enhance their suitability for a wide array of medical applications.

In essence, polyester proves to be a versatile and valuable material, demonstrating its presence in numerous products and showcasing its significance in advancing medical technologies and treatments.

The global demand for plastics continues to surge, and it is estimated that the quantity of plastics in circulation will escalate from 236 to 417 million tons annually by 2030 [78]. To prevent an increase in unintentional or deliberate release of plastic materials into the environment and mitigate environmental pollution, it is imperative to promote recycling and reuse of plastics in circulation. In 2016, a mere 16% of the polymers in circulation were collected for recycling, while 40% ended up in landfills, and 25% were incinerated (Figure 15). However, there has been a recent upswing in efforts by European countries to enhance recycling rates. For instance, in 2018, Europe successfully collected 29.1 million tons of post-consumer plastic waste. Though less than one-third of this waste was recycled, it still signified a doubling of the recycling quantity and led to a significant 39% reduction in plastic waste exports outside the European Union (EU) when compared to 2006 levels. It is noteworthy that a substantial portion (39.9%) of this plastic flow was attributed to packaging materials.

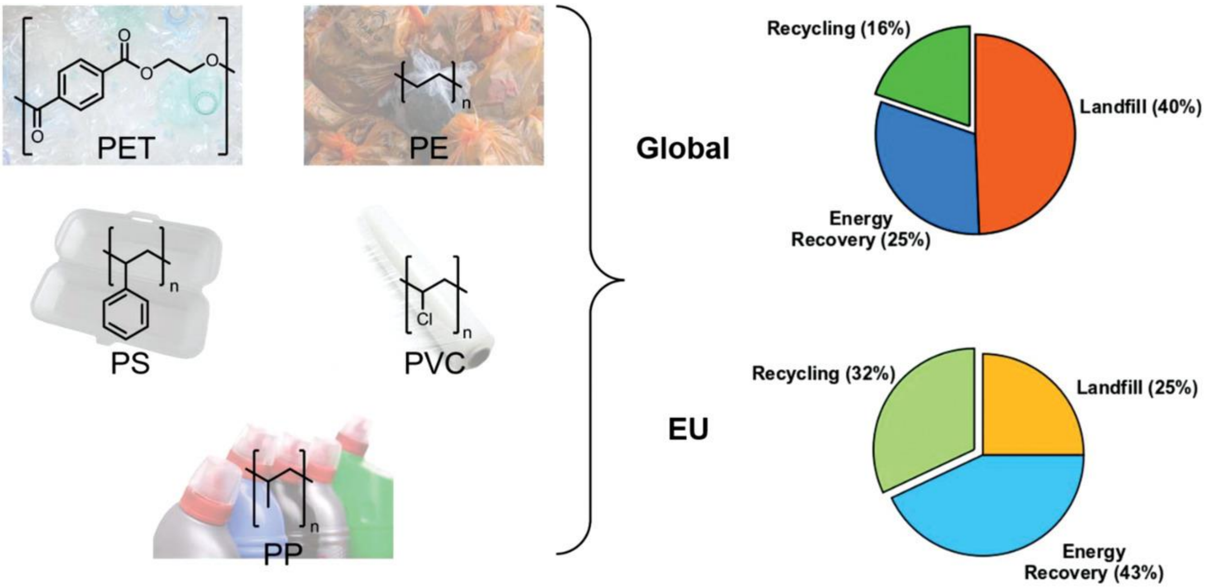


Figure 15. The main packaging polymers: poly(ethylene terephthalate) (PET), polystyrene (PS), polyethylene (PE), polypropylene (PP), and poly(vinyl chloride) (PVC) and current global and EU plastic waste management rates [78]

5.1.1. Recycling/Reuse and upcycling opportunities

Recycling, reuse, and upcycling of polyesters present both challenges and opportunities. One of the challenges in recycling polyesters is the difficulty in separating them from other materials. For example, when polyester is blended with other fibres such as cotton, it can be difficult to separate the two materials for recycling [79]. Another challenge is the lack of infrastructure and technology for recycling polyesters. While mechanical recycling is the most studied method of recycling, chemical and biochemical recycling methods are also being explored [80].

Despite these challenges, there are also multiple opportunities in the recycling, reuse, and upcycling of polyesters. Chemical recycling methods for polyesters such as poly(lactic acid) (PLA) and poly(ethylene terephthalate) (PET) are being developed, with a focus on upcycling and the use of metal-based catalysts [79]. These methods have the potential to modernize the plastics economy and create new materials from recycled polyesters.

While there are challenges in the recycling, reuse, and upcycling of polyesters, there are also many opportunities for innovation and progress in this field. By developing new technologies and infrastructure for recycling polyesters, polyester-made/-based materials/products can move towards a more sustainable and circular economy.

For the sake of completeness, the concepts of reusing, recycling and upcycling will be defined from the perspective of polyesters cycling as follows.

- Reusing: One way to reuse polyester products is to donate or sell them to others who can use them. For example, if someone owns a polyester jacket that no longer needs, that person could donate it to a charity or sell it to a second-hand store. This extends the life of the product and reduces waste.
- Recycling: Polyester can be recycled through mechanical or chemical processes. For example, PET bottles, the most common type of plastic bottles, can be recycled into polyester fibers. These fibers can then be used to create new products such as clothing, carpets, and other textiles. Many brands are now using recycled polyester in their products. For example, Camira Fabrics has been creating recycled polyester fabrics for over 20 years [80].
- Upcycling: Upcycling is the process of transforming waste materials into new products of higher value. For example, researchers at Northwestern University have developed a technique to enhance the effects of an enzyme that breaks down polyester into its fundamental parts [81].

Both reusing and recycling polyesters can help reduce waste and conserve resources. Upcycling takes this one step further by creating new products of higher value from waste materials.

There are several methods for recycling polyesters, including mechanical, chemical, and biochemical methods [80].

- Mechanical recycling is the most studied method of recycling and involves physically breaking down the polyester into smaller pieces, which can then be melted and reformed into new products.
- Chemical recycling involves breaking down the polyester into its constituent monomers using chemical processes. These monomers can then be purified and used to create new polyester products.
- Biochemical recycling involves using enzymes or other biological processes to break down the polyester into its constituent monomers. These monomers can then be purified and used to create new polyester products.

In addition to these methods, there are also emerging technologies for recycling polyesters. A novel methodology recently reported focused on the chemical separation of cotton/polyester blends. The method involves several steps, starting with the selection of suitable blends and pre-washing to remove contaminants. The textiles are then conditioned, and their weight and quality are assessed. The chemical processing utilizes a combination of solvents to dissolve the polyester fibres, while the cotton fibres are filtered and recovered. The dissolved polyester can be recycled back into fibre/textile production. The methodology offers the potential for high-performance textile development and a more sustainable future for the industry. However, it has some drawbacks, including the use of potentially hazardous chemicals and the need for specialized equipment and expertise [82].

5.1.2. Mechanical recycling

Mechanical recycling involves the recycling of plastic waste through a physical breakdown of the material into smaller fragments. These fragments are then utilized to manufacture new products, making it a crucial component in establishing an economically and environmentally sustainable plastic economy. Nevertheless, existing mechanical recycling techniques encounter constraints, such as high costs, reduced mechanical properties, and the production of inconsistent quality goods [78].

Procedures and obstacles associated with mechanically recycling five primary packaging plastics (poly(ethylene terephthalate), polyethylene, polypropylene, polystyrene, and poly(vinyl chloride)) can be briefly described within the framework of a circular economy.

The mechanical recycling process for primary packaging plastics involves shredding the plastic into small pieces, which are then washed, dried, and melted to create new products. It is important to note that the mechanical recycling process for each plastic type is limited by cost, degradation of mechanical properties, and inconsistent quality products.

Melt Blending.

Extrusion is a widely used and cost-effective method for mechanical recycling, producing regranulated material from common waste plastics. It involves using heat and rotating screws to soften the plastic, leading to chain degradation and reduced mechanical properties. The susceptibility to degradation depends on polymer characteristics and extrusion conditions. Thermo-oxidative reactions are influenced by the polymer structure and oxygen diffusion. Recycled plastics often experience reduced strength and elongation. Proper polymer sorting is crucial to avoid contamination and ensure efficient recycling.

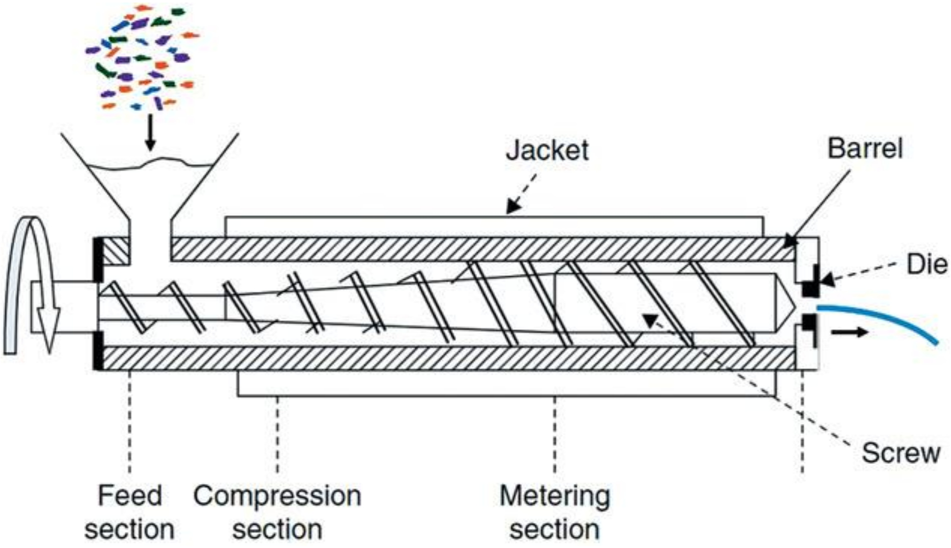


Figure 16. Schematic representation of a single screw extruder [83]

Waste Sorting for Recycling.

Plastic waste sorting involves automated and manual processes, utilizing Near infrared (NIR) technologies and optical colour recognition. Other methods include X-rays, density, electrostatics, and manual sorting. Polymer marking systems could improve sorting accuracy and value retention, but their viability in melt extrusion is uncertain. Developing marking systems with anti-degradation effects is crucial for a circular economy of plastics.

Stabilizer Use in Plastic Recycling.

Stabilizers, such as antioxidants, are used during extrusion to inhibit free radical reactions and prevent oxidation in both mechanical recycling and product use. There are two types of antioxidants. Primary antioxidants act as radical scavengers, protecting polymer chains during their lifetime, while secondary antioxidants prevent chain degradation during melt processing. Stabilizers can also protect polymers from UV-based degradation. However, additives like antioxidants complicate the recycling process, causing issues in waste sorting, migration, and aesthetics. For example, carbon black, used for colouring and UV protection, hinders waste sorting and causes discoloration in recyclate. Recent developments include incorporating active antioxidants in food packaging, eliminating the need for antioxidant incorporation inside food products. Stabilizers can migrate and cause areas of degradation in contaminated materials. Research rarely explores antioxidant stability during repeated extrusion cycles, highlighting the importance of considering end-of-life recycling in polymer design.

Polymer Blends in Recycling.

To address sorting challenges in the plastics industry, value must be extracted from impure feedstock like mixed polymer streams. However, these blends often lead to weakened materials due to phase immiscibility and demixing. Compatibilizers play a crucial role in enhancing the value of recyclate by promoting phase adhesion and stress transfer. Polymer blending requires similar polarities, and reactive extrusion processes can improve blend miscibility.

Mechanical Recycling of Poly(ethylene terephthalate) - PET. Virgin PET (vPET) is known for its outstanding mechanical properties, processability, and barrier properties, making it a popular choice for packaging, particularly in food-grade applications. vPET exhibits high ductility and impressive elongation at break values, often exceeding 80%. However, these mechanical properties rapidly decrease by a factor of 4 when the PET is mechanically recycled. This sharp reduction in properties is a result of the material's susceptibility to thermo-oxidative and thermo-mechanical degradation, as well as hydrolytic scission of the polymer chains during the recycling process.

Mechanical Recycling of Polyolefins.

During the mechanical processing of polyolefins, degradation occurs, leading to the formation of various carbon-based molecules like alcohols, aldehydes, ketones, acids, cyclic ethers, esters, and short-chain hydrocarbons. The three main polyolefins used in packaging, HDPE, LDPE, and PP, exhibit different degradation mechanisms from each other and other packaging polymers. Radical attack generates macroradicals along the polymer backbone, which undergo β-scission to form other macroradicals. Intramolecular radical transfer leads to the formation of various radical species, resulting in shorter, branched, or crosslinked polymer chains. When polymer macroradicals react with oxygen-based radicals, carboxylic acid, carbonyl, and hydroxyl end groups are introduced, potentially promoting further degradation. HDPE and LDPE exhibit higher crosslinking rates, while PP is more susceptible to chain scission. Polyolefin chains are primarily attacked in the amorphous phase of the polymer, as oxygen struggles to diffuse through highly crystalline domains.

Mechanical Recycling of Poly(vinyl chloride).

Poly(vinyl chloride) (PVC) is widely used in the food and construction industries due to its robustness, lightweight, flexibility, and excellent barrier properties to oxygen and water. However, at the end of its life, PVC degradation results in the release of chlorinated products into the environment. The degradation mechanisms during recycling include thermo-oxidation, crosslinking, functionalization of chains, and hydrodechlorination. Pyrolytic treatment of PVC is discouraged due to the potential release of highly toxic and corrosive HCl gas, which can have detrimental effects on both the environment (e.g., acid rain) and the recycling plant (e.g., reactor corrosion). To enable effective mechanical recycling, PVC waste streams must be pure and highly stabilized to prevent unwanted degradation.

Mechanical Recycling of Polystyrene.

Polystyrene (PS) exists in three forms: solid, expanded foam, and a polybutadiene reinforced form (HIPS), all commonly used in packaging. PS recycling poses challenges due to its low densities. Solid PS can be mechanically recycled into other useful products, while expanded polystyrene (EPS) requires de-foaming to reduce its volume before reprocessing. De-foaming can be achieved using solvent-based or mechanical methods. The use of the bio-derived solvent, d-limonene, extracted from citrus fruits, is a promising technique for EPS de-foaming. It reduces EPS foam volume significantly and acts as an antioxidant, protecting the chains from radical-induced scission. Although d-limonene is expensive, it is food-derived and potentially more environmentally friendly than other solvents like toluene. Moreover, it selectively dissolves EPS while preserving expanded polyolefins and labels. Alternatively, other natural oils like star anise oil, eucalyptus oil, thyme oil, and chamomile oil can be used to reduce EPS foam volume without affecting molecular weights. For eliminating solvent cost and impact, mechanical methods, like an apparatus to mechanically reduce the size of foamed polystyrene, can be employed. Recycled EPS (rEPS) can be re-gassed to enhance its foamed characteristics, but the added cost compared to virgin polymer remains a barrier to higher recycling rates.

Mechanical Recycling of Polyester-based fabrics.

Mechanical recycling is conducted through two main paths, each employing different recycling mechanisms. The first path involves the melt-extrusion process, where waste is subjected to shredding, crushing, and grinding, followed by melting and re-extrusion to obtain fibres. These fibres can then be further processed into yarns or non-woven panels. For synthetic fabrics like polyester or nylon, they can be transformed into flakes and then converted back into fibres through melt-extrusion, either directly into fibres or by first pelletizing the flakes and then extruding them into fibres. The second path in mechanical recycling includes cutting, shredding, and carding of fabrics to open up the fibres. These fibres are utilized in various building and industrial applications. Shredded or crushed textile waste can be heat-pressed to create panels or sheets used for thermal and noise insulation, reinforcement materials, and industrial applications [80].

5.1.3. Chemical recycling

Chemical recycling of polyesters is a process that involves the use of chemical transformations such as hydrolysis, transesterification, hydrosilylation, among others, to either recapture virgin monomer (closed-loop) or directly convert it into other useful synthetic chemicals/feedstocks (open-loop). The process is based on the polymer backbone bearing functionality susceptible to cleavage, for example, ester linkages found in polyesters. The potential benefits of chemical recycling relative to mechanical recycling include removing material downcycling, promoting the long-term retention of material value within the plastics economy, potential for upcycling plastic waste, enabling value-added chemicals to be accessed for enhanced economic performance, and access to raw virgin feedstocks, such as lactic acid from PLA, whilst preserving product quality [84].

Chemical recycling offers two distinct paths for recycling plastics. The first path involves depolymerization and repolymerization. In this process, plastic polymers, like polyester, are broken down into their monomer units and then re-polymerized into new fibres or materials. Ionic liquids are used as solvents to dissolve cellulose fibres, such as cotton or viscose, in the dissolution route. These solvents facilitate the dissolution of cellulose by breaking the intramolecular hydrogen bonds. N-methylmorpholine N-oxide (NMMO) is a commonly used solvent for cellulose dissolution as it allows complete dissolution without any degradation. The dissolved cellulose in the ionic liquid can be regenerated into various forms, including man-made cellulose fibres, films, aerogels, or hydrogels. Similarly, polyester can be dissolved using chemicals such as dimethylisophthalate, dimethylterephthalate, or methyl-p-toluate, and subsequently recovered and re-spun back into polyester. Textile products often consist of fibre blends rather than a single raw material, and researchers have explored solvent-based methods for separating these blends. For instance, 1-allyl-3-methylimidazolium chloride can be utilized as the ionic liquid to selectively dissolve cotton and recover polyester with a high yield in cotton/polyester blend separation. Additionally, attempts have been made to separate cotton/nylon blends and recover nylon and cellulose through a dissolution and filtration route [80].

5.1.4. Biochemical recycling

Ester bonds are prevalent in both petrochemical-derived plastics and bio-based polymers. Common plastics containing these bonds include polyethylene terephthalate (PET), polycaprolactone (PCL), poly-lactic acid (PLA), and various others. Notably, enzymes capable of degrading these plastics have been identified. This may be attributed to the abundance of ester bonds in natural polymers found in lipid- and phenolic-based barriers present in plant cell outer layers. Enzymes known to degrade natural polymers, such as cutinase enzymes from *Thermobifida* spp., have also demonstrated the ability to degrade synthetic compounds like PET. Moreover, several lipases and esterases have been found to be effective in degrading one or more of the aforementioned polyesters [85].

Enzymatic degradation and conversion of plastics offer a promising avenue for achieving sustainable recycling of plastics and their building blocks. However, the search for efficient enzymes capable of large-scale and cost-effective plastics degradation presents numerous challenges. Existing research has showcased a variety of experimental setups, but often lacks comprehensive investigations into the microbial species with plastics degrading capabilities and their corresponding enzymes [76].

The proposed framework encompasses the following key steps Figure 17:

- Collection of samples and isolation of microorganisms displaying plastic-degrading capabilities.
- Screening of microorganisms to assess their plastic-degrading activity.
- Identification and optimization of plastic-degrading enzymes for enhanced performance.
- Thorough characterization of the enzymes and their specific properties.
- Scaling up of the enzymatic process to enable large-scale plastics degradation.
- Evaluation of the efficiency and sustainability of the enzymatic process.

This comprehensive framework serves as a valuable guide for identifying and fine-tuning plastic-degrading enzymes, making it applicable for various applications, such as biorecycling, bio-upcycling, bulk degradation, or bioremediation purposes [76].

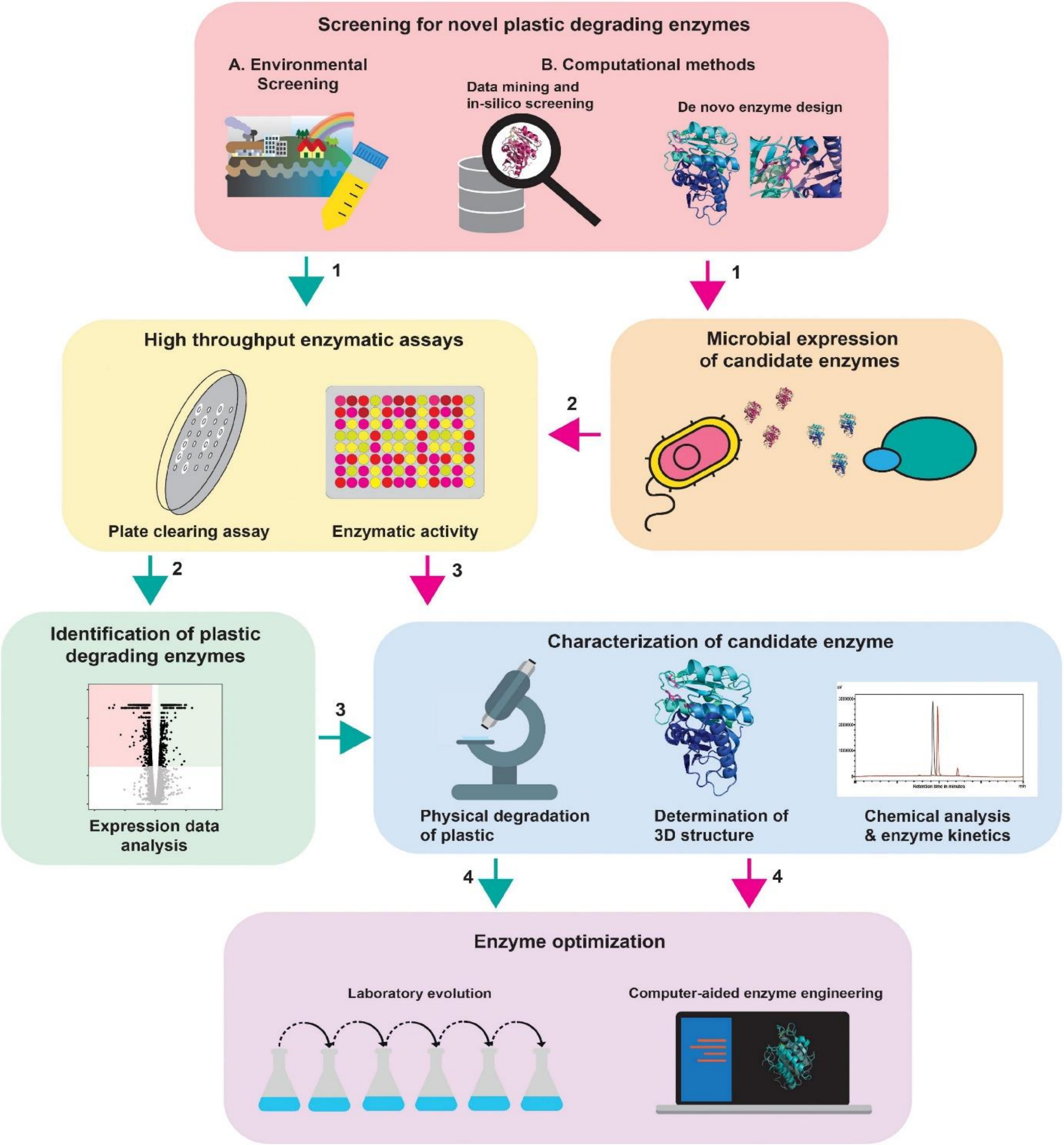


Figure 17. Comprehensive workflow for the identification of plastic degrading enzymes [76]

Biorecycling and bio-upcycling present promising alternatives to traditional mechanical recycling methods, offering the advantage of preserving product quality and minimizing waste. The use of purified enzymes or enzyme cocktails can effectively catalyze the depolymerization process. Once plastic-degrading strains or enzymes are identified, characterized, and enhanced, their application becomes crucial for the degradation of plastics.

5.1.5. Potential Pathways and main actors

Plastics have played a significant role in human development due to their strength and durability, but their widespread use also contributes to environmental pollution when they reach the end of their life [84].The traditional linear model of plastic production, coupled with reliance on finite fossil feedstock, worsens environmental issues (Figure 18).

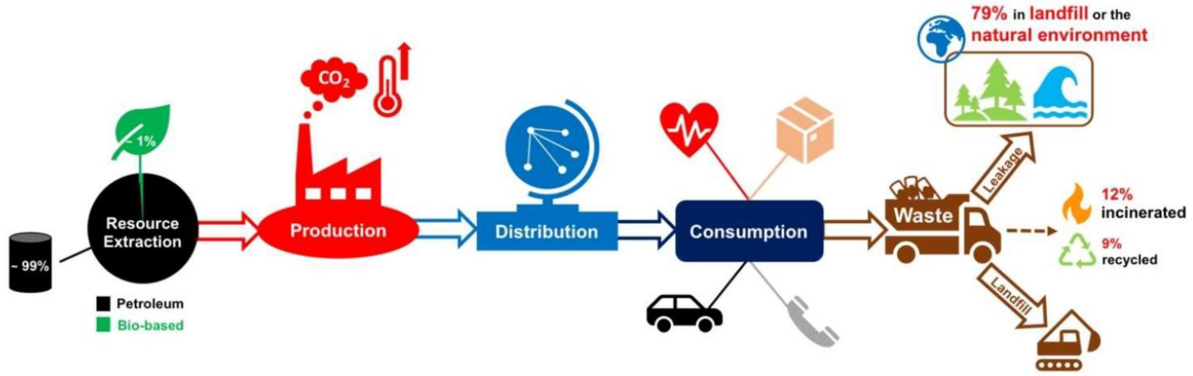


Figure 18. Linear model of a petroleum-based plastics economy [84]

The recycling rates for plastic packaging wastes exhibit significant variation across Europe, with an average of 42% in 2018. Opting for recycling instead of incineration can lead to a reduction in emissions, estimated to be around 1.1-3.0 tonnes of CO2-equivalent per tonne of managed plastic waste. The collection and recycling rates differ based on the types of polymers and their applications. However, accurate data on recycling rates for plastic waste in waste electrical and electronic equipment, textiles, and end-of-life vehicles remain limited [27].Table 9 provides an overview of the sources of various plastic wastes as Secondary Raw Materials (SRMs).

Table 9. Source of plastic waste as a secondary raw material [27]

Subgroup pf waste feedstock	Application or end-of-life product	Material group	Secondary raw material
Packaging waste	Plastic packaging (e.g., bottles, bags, etc.)	Thermoplastics (PET, HDPE, PVC, LDPE, etc.)	Mixed plastics, recycled monopolymer flakes, regranulates and regrinds, monomers, pyrolysis oil
Technical plastic waste	Automotive, EEE, building and construction products	Thermoplastics (ABS, HIPS, PC, etc.)	Mixed plastics, recycled monopolymer flakes, regranulates and regrinds, monomers, pyrolysis oil
Waste textiles	Carpets, clothing	Polyester, nylon, acrylic, polyamide	Recycled polyester, polyamide, nylon yarn, recycled polyester chips
Fibre-reinforced wastes	Wind turbine blades, boats	Thermosets	-

Note: ABS, acrylonitrile butadiene styrene; EEE, electrical and electronic equipment; HDPE, high-density polyethylene; HIPS, high-impact polystyrene; LDPE, low-density polyethylene; PC, polycarbonate; PET, polyethylene terephthalate; PVC, polyvinyl chloride.

The packaging sector accounts for the majority of plastic demand, representing approximately 40% of the total, followed by the building and construction, automotive, and electronics sectors. Although textiles also consume significant amounts of plastics, data on this sector's usage is not readily available in the available statistics. The management of plastic waste data remains uncertain. Europe generates about 45 million tonnes of plastic waste annually, significantly higher than the typical range of 25-30 million tonnes reported. The amount of plastic waste "collected for recycling" does not always align with the actual recycling figures. Some fractions are exported, while others end up in incineration or landfills. The revised PPWD enforces stricter reporting rules for plastic recycling, leading to a potential decrease in the reported average plastic packaging recycling rate for the EU [27].

- Several factors hampering the production of high-quality secondary plastics have been identified as follows:
- Plastic wastes are often complex and heterogeneous, containing different polymers, additives, and potentially other materials like metals and paper.
- Polymers vary in their recyclability, and some cannot be recycled together in the same waste stream.
- The presence of hazardous materials in plastics, such as additives, colorants, plasticizers, and stabilizers, poses challenges for recycling processes. Some of these substances are listed as substances of very high concern, imposing strict limits on their content in recyclables.
- The low traceability of the chemical content in plastic products further complicates recycling efforts and reduces the demand for recycled plastics.
- Contamination is a common issue, as plastics may become contaminated during use, either by food waste or other chemical substances that come into contact with the plastics.
- Downcycling occurs when recycled content is of lower quality than the original product, or when recyclates are used in products of lower value than the original, limiting subsequent recycling options.
- The low price of primary materials and the costs of sorting and processing create a price premium on products made from secondary plastics. The volatility of primary material prices also hinders stable development in the SRM (Secondary Raw Materials) market.

- During recycling, the polymer length may degrade, reducing the number of recycling loops. The addition of virgin material to recycled plastic can extend the number of loops in some cases.
- Thermoset polymers have limited mechanical recycling options, resulting in very low recycling rates for these materials.

There is a growing demand for including recycled material in plastics. Many businesses and brand owners have set voluntary targets for recycled plastic content, with the Circular Plastics Alliance aiming to achieve 10 million tonnes of recycled plastic content on the market by 2025. Several drivers behind this demand include contributing to EU Single-Use Plastic Directive targets, accelerating the transition to a circular economy, ensuring sustainability for the industry, and taking environmental responsibility seriously for customers.

However, companies seeking to use recycled plastics face challenges in finding sufficient and stable volumes of recycled plastics at the required quality. Safe and secure supplies of raw materials are crucial, and the lack of End-of-Waste (EoW) criteria is seen as a barrier in the industry, causing ambiguity about when waste ceases to be waste. The European Commission plans to develop EoW criteria for plastic waste and textiles by 2022 and 2023, respectively.

The Commission has completed a scoping assessment to determine the priority list of waste streams for EU-wide end-of-waste criteria development, following the Circular Economy Action Plan. Plastics and textiles have been identified as the top two candidate streams. The development of end-of-waste criteria for plastic waste will start in Q2 2022 and is expected to conclude by Q1 2024. Work on end-of-waste criteria for textile waste will commence in 2023 [86].

The most in-demand plastic recyclates include high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene, and PET, with PET being highly sought-after in sectors beyond plastics. Demand for recycled PET (rPET) is high, exceeding supply. The price of recycled plastic varies significantly based on factors like contamination, hazardous content, material degradation, colour, and odor. The demand and price for regranulated engineering plastics are consistently high if the quality is good (Figure 19).

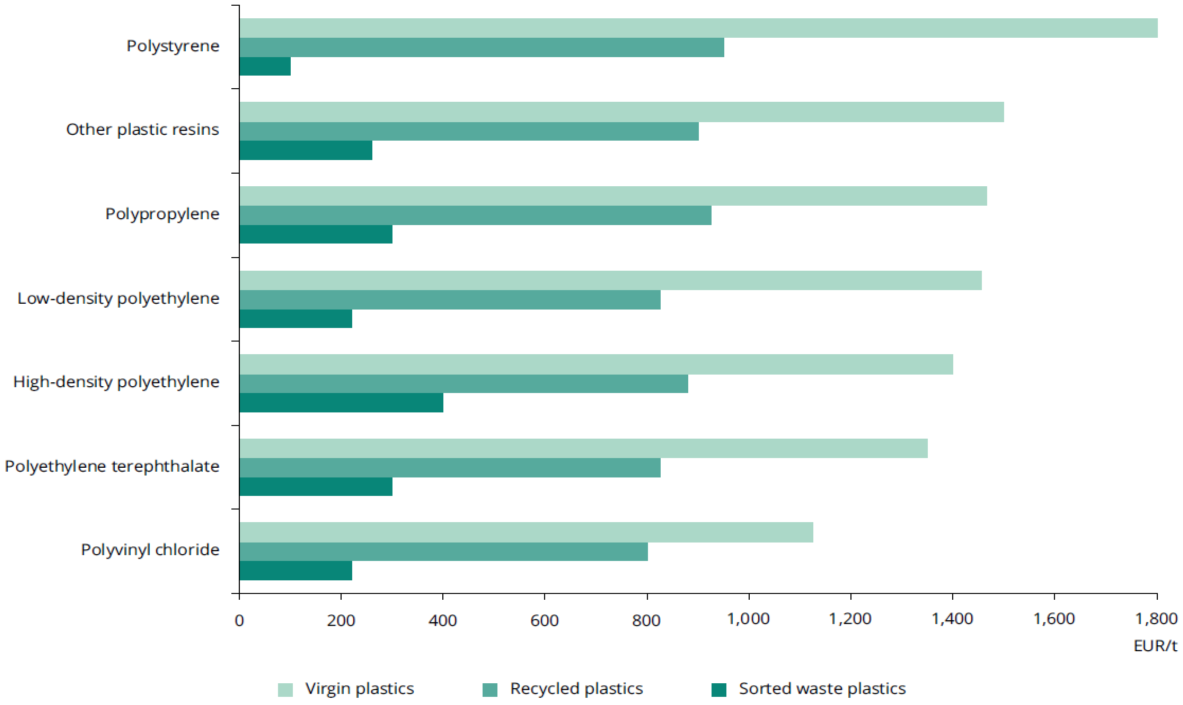


Figure 19. Difference in value of unsorted, sorted and recycled plastics [84]

Polyethylene terephthalate (PET) is a well-established plastic with a strong market presence. It is commonly used in beverage bottles, food jars, shampoo bottles, and mouthwash bottles. In 2017, the demand for PET was 3.9 million tonnes, and 1.9 million tonnes of PET bottles were collected and recycled (some in textiles). The average recycled content in PET bottles in Europe has been approximately 11%. With the upcoming requirement in the Single-Use Plastics Directive, which mandates at least 25% recycled content in PET bottles by 2025 and 30% by 2030, the demand for recycled PET is expected to rise significantly, driving prices higher than primary PET [87].

Plastic recyclers face tough competition with virgin plastic producers, making recycling economically challenging. Fluctuations in material quality and price significantly affect the viability of recycled plastic markets. Virgin resin prices, tied to volatile oil prices, add to the complexity. To succeed, recyclers focus on cost-cutting and producing high-quality materials for valuable applications like food-grade packaging. Preventing downcycling and promoting closed-loop systems, where plastics are recycled back into the same value chain, can address supply traceability and quality concerns. While the rPET market works relatively well, others, especially mixed plastics and composites, struggle, leading to an overall imperfect secondary plastics market.

5.2. Wood

5.2.1. Recycling/Reuse and upcycling opportunities

Wood is one of the main renewable natural resources available in the world, which is only partially utilized. As a challenge and an opportunity, the production of high-quality local timber from sustainable forest management also represents an opportunity for the economy of public and private forest owners.

The wood value chai includes steps from generation of wood waste to its end of life, including transport, collection, treatment and processing. Wood waste is mainly generated in the timber, construction and demolition, and packaging industries [88]. About the secondary raw materials and waste from wood industries, the types of waste produced include small wood fragments such as chips, sawdust and shavings, as well as larger assortments such as rejects or offcuts. These wastes often contain additives or contaminants because the wood may have been painted or treated during the manufacturing process.

Figure 20. Example of wood products value chain.

Extraction of raw materials

The raw material has a dual origin, as it is sourced from both forestry operations and other regions/countries, as well as from the utilization of wood by-products.

Wood transformation and distribution

The extraction process is usually accompanied by a basic transformation of the raw material, which takes place in the vicinity of the forest operations, starting from round logs in sawmills or logs in sawmills or unrolling lines. The final production or assembly processes require the intervention of agents that integrate and distribute the materials, which is usually carried out by transformers.

Marketing

Developed largely by the manufacturing companies themselves, marketing is also carried out by a large number of national and international prescribers and companies, which are key to the development of the sector.

Use

Used in several sectors: Construction, Furniture, Packaging, Energy, etc.

End of Life

An important difference in the potential for collection and reuse of wood waste is whether the wood is hazardous (i.e., contaminated) or non-hazardous. Non-hazardous wood waste requires little or no treatment or processing, apart from adaptation to the right size for integration into the final product. The wood residues are sized to be integrated into the final product.

Different classifications exist in Europe. One example is the classification methodology from The Wood Recyclers Association [89], that classifies the wood waste into four different categories:

- Grade A Pre-Consumer Waste Wood and untreated wooden packaging = Clean un-treated
- Grade B Business waste wood = Treated Non-hazardous. Contains chemically treated used wood that does not contain "halogenated organic compounds". Examples are raw material for panels such as chipboard and some types of fiberboards.
- Grade C Municipal waste wood = Treated Non-hazardous. Mainly used for bioenergy generation.
- Grade D Hazardous waste wood = Treated hazardous. Requires disposal in specialised facilities.

According to the characteristics of different wood wastes derived from wood industries, there are several technologies and techniques to collect and treat the flow. The description of most common solutions is here:

Collection

Wood waste is systematically collected and sorted based on its quality grade, right at the initial stages of the value chain. Subsequently, depending on its grade, the wood waste undergoes diverse treatment methods, which encompass recycling it into boards or pellets, harnessing its energy through incineration, or processing it in specialized facilities.

The collection of wood waste takes various routes, contingent on its origin, quantity, and level of sorting. Household wood waste is predominantly gathered at municipal waste centers or through bulky waste collection programs facilitated by local municipalities, particularly when it concerns furniture waste. On the other hand, construction, demolition, and industrial wood waste can either be collected by waste management companies utilizing containers or be managed directly by the producers themselves.

Furthermore, informal methods of wood waste disposal are also observed, such as small-scale burning in boilers conducted by producing companies or their employees.

In 2012, the UK Wood Recycling Association (WRAP) prepared a report that outlined four potential collection strategies in the UK, which can be extrapolated to encompass wood waste collection on a broader scale:

- Municipal waste collection points, especially oriented to promote the recycling of wood waste in small businesses and households.
- Waste managers, who recover wood waste for profit. The collection is carried out by the waste managers themselves, who then carry out the recovery process.
- Reverse logistics for wood-based businesses - Deliveries of wood products to wood-based businesses are sometimes combined with a wood residue collection and transportation service. This allows wood suppliers to provide a collection route to reuse large quantities of wood as raw material or fuel, or to supply other markets.
- Wood recovery in composting. There are compost producers who receive significant tonnes of wood waste as they have mostly suitable sites and facilities for wood recovery.

Sorting

Before wood waste is recycled, it undergoes an essential sorting process after collection by wood recycling specialists. The price of waste wood is determined by its quality, so sorting and grading is necessary to meet the desired standards. Sorting is incorporated into the collection system by pricing incoming wood waste according to its content, which gives waste producers an incentive to separate lower quality waste.

Subsequently, the wood waste undergoes further sorting and sorting procedures. The extent of sorting efforts in sorting facilities depends on the type of waste collection, taking into account factors such as quality and impurities. Various techniques, such as visual inspection, mechanical sorting, magnetic separation and gravity screening, are used to distinguish treated wood and other contaminants from wood waste. These sorting methods are applied at different stages along the wood waste treatment chain.

- Shredding, screening and extraction of non-ferrous metals
- Wood waste is shredded and screened. These sites require handling equipment (grapple shovels, telescopic shovels, loaders), one or more fix or mobile shredders (slow, rapid) and screening equipment.
- Wood waste is first shredded and screened at these sites, using specialised handling equipment such as grapple shovels, telescopic shovels, and loaders, together with stationary or mobile (slow or fast) shredders and screening machinery.
  -Handling: Construction sites require suitable handling equipment to effectively feed the crushing equipment. This may be grapple-equipped shovels or bucket loaders. Shovel loaders also play a crucial role in feeding crushers and screens, as well as handling materials such as fine fractions and crushed waste and loading trucks for transport.
- Shredding: The main purpose of shredding is to reduce the particle size of the incoming wood waste and to facilitate the removal of any iron content. Slow shredding is normally carried out before fast shredding to avoid breakages in the fast shredder and to improve metal recovery. The crushers are usually equipped with 'hammer' mechanisms and one or more magnetic rolls for iron removal. These two crushers are installed in series, with conveyor belts transferring material from the slow crusher to the fast crusher.
- -Screening: Although not always applied, screening is used depending on the specific needs of the end user. In these cases, operators typically use a simple drum screen, which separates the incoming product into fine and coarse fractions. The mesh used in the drum screen is usually round or square, with mesh sizes ranging from 10 to 30 mm. When a different mesh size is required, the drum is replaced accordingly.
- Mechanized sorting: Although not as common, mechanized sorting enables a more precise sorting process through a series of separation equipment, and occasionally manual sorting tables. There are two primary scenarios:
- Mechanized sorting chains designed to separate mixed waste from economic activities and municipalities (e.g., wood, plastic, ferrous materials). These chains are utilized in sorting centers.
- Mechanized sorting chains dedicated to processing wood waste exclusively. These chains are employed by wood panel manufacturers (in the "wood panel industry") or industries that produce energy from wood waste.

Valorization

The last step in the value chain is valorisation of wood waste. The requirements of wood waste are specific to each way of valorisation. However, many undesirable parameters are common, such as heavy metal, chlorine and others. Most of wood waste is recovered in following industries: recycling in wood-based panels, paper and paperboard and energy. The last step in the value chain is the recovery of wood waste. The requirements for wood waste are specific to each form of recovery because many undesirable parameters are common, such as heavy metals, chlorine and others.

- Mechanical recycling: Wood waste recycling is the processing of discarded wood materials into new products. The waste is sorted and separated according to its quality and suitability for various applications. Clean, untreated wood waste is usually chipped or shredded into smaller particles, which can then be used to make recycled wood-based panels, composite materials or paper products. Recycled wood products can be used for construction, furniture making, packaging and other applications. Recycling wood waste helps reduce the demand for virgin wood, conserving natural resources and mitigating the environmental impact of logging and deforestation.
- Energy recovery: Wood waste is a valuable source of renewable energy. Using energy recovery techniques such as incineration or gasification, wood waste is burned in controlled environments to generate heat or electricity. This process helps to divert wood waste from landfills and, at the same time, produces sustainable energy. The energy generated from wood waste can be used to power industries, commercial buildings and even supply electricity to the grid, reducing dependence on fossil fuels and reducing greenhouse gas emissions.
- Composting: Some types of untreated wood waste, such as sawdust, wood chips and bark, can be composted. Composting wood waste involves mixing the materials with other organic matter, such as food scraps or garden clippings. The composting process breaks down the organic components, producing nutrient-rich soil amendments. This compost can be used as a natural fertiliser in agriculture, horticulture and gardening, improving soil fertility and plant growth.
- Biomass conversion: Biomass conversion processes, such as pyrolysis and biochemical conversion, can transform wood waste into biofuels and other bio-based products. In pyrolysis, wood waste is heated in the absence of oxygen, resulting in the production of biochar, bio-oil and syngas. These products can be further processed to create renewable fuels or chemicals. Biochemical conversion involves the use of micro-organisms to break down wood residues into biofuels such as ethanol or biogas. These biofuels can be used in transport, heating and other applications, providing greener alternatives to fossil fuels and reducing carbon emissions.

According to the “Analysis of certain waste streams and the potential of Industrial Symbiosis to promote waste as a resource for EU Industry” [90], Industrial symbiosis (IS) is exercised by all forest-based industries, whether it is in the form of reuse by a producer itself (IS1), through the direct sale between one company and another (IS2), or through a collector or specialised company that refines, recycles or treats the material and sells it to the market (IS3). Nevertheless, there is room for prolonging the wood lifecycle.

In this report, a number of possible improvements for wood waste could negatively affect the successful marketing of secondary wood raw materials:

Competitiveness

The escalating demand and increasing value of wood waste are prompting certain industries to explore the potential of industrial symbiosis (IS2) networks and enhance their waste collection efficiency. However, for other industries, this trend presents a barrier to implementing industrial symbiosis. Several interviewees have identified a key challenge, which stems from the growing attractiveness of wood and wood waste for energy generation due to subsidies offered in this sector. These subsidies are motivated by Europe-wide targets to achieve 20% renewable energy by 2020, with biomass energy playing a significant role. The rising demand from the energy sector is depleting the supply of wood by-products and wood waste, leading to higher prices for wood waste. Consequently, this creates competitive pressures for other users of wood waste, such as the panel and pulp industries. Interviewees from the pallet and packaging industry also emphasize that the price increase in wood waste discourages innovation and the development of new products, as it becomes less economically viable to do so. Moreover, these challenges are further amplified by the aftermath of the financial crisis, which has caused a significant decline in demand across various industries.

However, the sawmill industry views the increased competition resulting from energy generation favorably. Almost all of the by-products from the sawmill industry are sold to vertically integrated local wood industries, representing a significant source of revenue for sawmills. The decline in paper consumption over the past decade has reduced the demand for by-products from the pulp industry. Therefore, the emergence of the bio-energy industry and the associated price increases have helped sawmills sustain their operations.

Legislation can also act as a driving force for industrial symbiosis. In the packaging industry, the current EU directive focusing on wood packaging (94/62/EC) sets a target of 15% recycling, promoting IS initiatives. Additionally, legislation sometimes prohibits the recycling of specific types of waste, with variations at the national level. For example, in Belgium, it is prohibited to recycle hazardous wood waste classified as the lowest C-category, and it must be incinerated. Another instance is the European and national regulations on "food contact materials," which restrict the use of non-plastic materials like wood.

Financial rewards

Financial incentives play a pivotal role in driving the establishment of industrial symbiosis (IS) networks, offering increased revenues or cost reduction opportunities. Within the pallet sector, interviewees highlight that while the current economic benefits for pallet producers from selling wood waste may be somewhat limited, the landscape is gradually shifting. Some pallet repairers now receive modest payments from collection agencies for their waste wood, a departure from the previous scenario where they had to bear collection costs. Additionally, the demand for non-hazardous wood waste has surged, resulting in the furniture, packaging, and construction sectors paying less for collecting higher quality wood waste while offering more for hazardous wood.

However, a specific challenge emerges concerning economic rewards due to economies of scale and scope within the value chain. Many interviewees express a keen desire to directly market their by-products to other companies, but the individual quantities generated at their facilities often fall short of being economically feasible for transportation to a central collection point. Factors like the substantial size-to-value ratio of by-products, the diversity of wood species, and the remote locations of facilities further constrain economies of scale and scope for effectively utilizing wood waste, thereby impacting the viability of the business case. While optimizing wood waste flow through better collection and coordination can enhance economies of scale and scope, transport costs remain a limiting factor, as wood waste typically only travels within a 25-40 km radius, thereby confining direct exchanges to a more localized context.

Transport costs

Based on insights gathered from interviews during the study on challenges in promoting industrial symbiosis in the wood waste sector, transportation costs emerge as a significant factor warranting careful consideration [90].

In the pallet sector, two primary barriers to industrial symbiosis become evident. Firstly, the dispersed nature of pallet production and repair facilities, combined with the transportation costs relative to the value of wood waste, poses a formidable challenge. Industry representatives express their desire to establish a direct connection with the panel industry, bypassing waste collectors as intermediaries, to increase revenues from the relatively clean waste generated by pallets. However, the current limitation lies in the limited waste volumes generated at each repair center. While waste collectors play a crucial role in merging various small-sized waste streams, centralizing waste allocation might incur extensive transport distances, rendering it cost-ineffective.

Similarly, large-scale consolidation presents challenges for the sawmill industry. Sawmills are sparsely located and individually generate small amounts of waste. The decentralization is further influenced by their proximity to forests and the variation of tree species in different regions. Additionally, the sawmilling industry primarily operates locally, with prices determined within the local market, making long-distance transport economically impractical. Consequently, collectors play a pivotal role in facilitating waste management.

Forest-based industries also face obstacles due to the low quantity of waste. In the packaging industry, wood waste is categorized into A (clean or untreated), B (painted or glued), AB (a mixture of A and B), or C (hazardous) categories according to legislation. The collection and sorting of these waste categories are highly dependent on associated costs, including sorting, shredding, and transportation, along with the potential revenue. In cases where costs are high, it may be more economically viable to utilize the waste for energy generation rather than recycling it for other purposes, such as panels.

However, interviewees suggest that the pallet industry has been exploring the reuse of its wood waste for pallets and other products. Additionally, significant opportunities for improvement exist in the packaging industry, where both light and heavy packaging is often used only once or a few times. Unlike the pallet sector, the packaging sector lacks clear ownership of the waste stream, leading retailers and industrial end-users to frequently dispose of packaging rather than reusing it. Addressing this challenge presents an area with substantial potential for improvement in wood waste management.

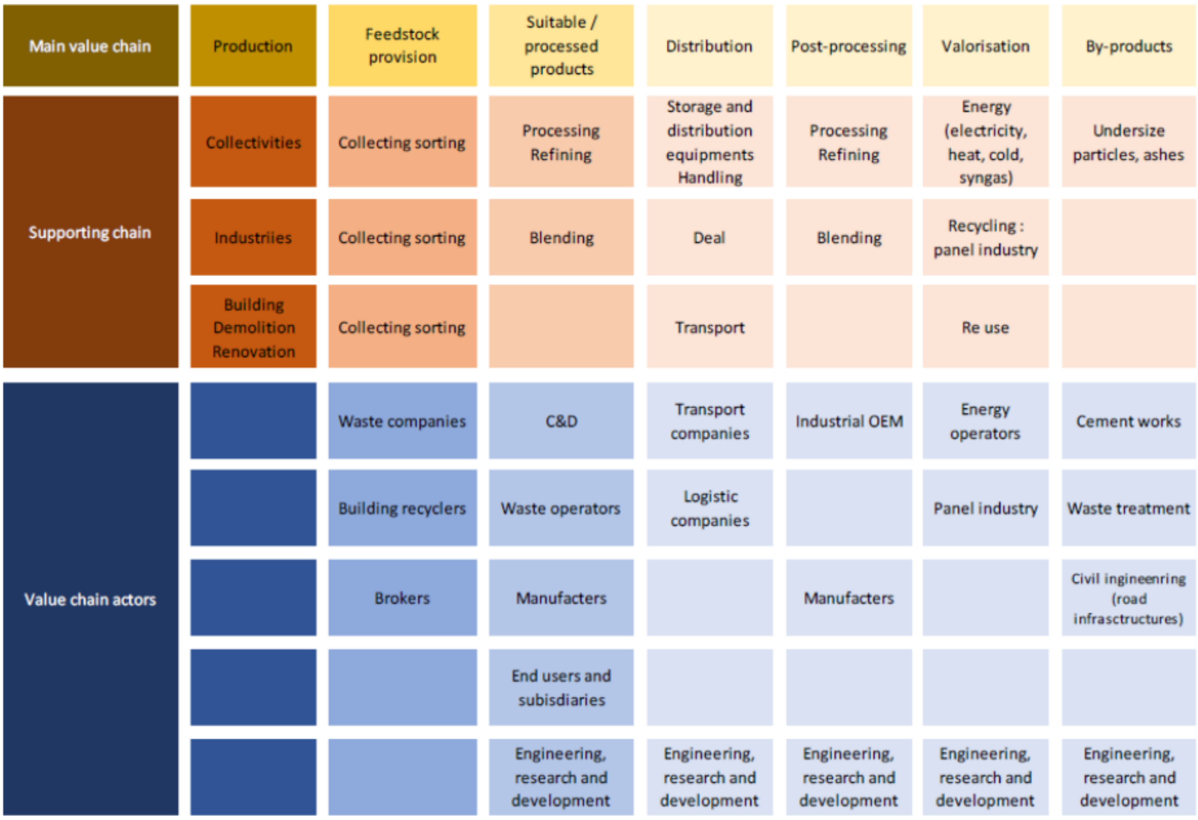
Taking into account all the information about this waste flow, some general opportunities have been identified to improve processes and boost the commercialisation of secondary wood raw materials in different ways:

- Reuse opportunities
  - Encourage producers to look for opportunities to reuse the waste wood before other uses following the waste hierarchy legislation, with new policies and legislation to encourage the reuse before other uses.
  - Main actors: Public administrations, companies.
  - Create new transfer plants or collecting centres to separate the wood waste according to the quality and characterization and save the secondary raw materials that are able to be reused.
  - Main actors: Public administrations, companies.
  - Develop new platforms and systems that allow access to updated information about wood secondary raw materials from different origins (companies, industries), to boost the flow of this materials to other industries that can utilize it.
  - Main actors: Public administrations,
- Recycling opportunities
  - Improving sorting processes to optimize the valorisation ratio, before the valorisation processes.
  - Main actors: wood waste managers.
  - Encourage producers to recycle with new policies and legislation, as producer responsibility and other obligations, to increase the valorisation rates.
  - Main actors: wood waste producers.
  - Encourage the sorting in construction sector, separating the wood waste from other waste flows in collection centres, to increase the valorisation rate in waste managers.
  - Main actors: wood waste producers, waste managers.
  - Enhance the quality of post-treated wood waste in waste management facilities. The wood waste supplied to the market often fails to meet the required standards, so greater efforts should be made in the valorization processes (such as shredding, screening, removal of ferrous and nonferrous materials, NIR, XRF, blending, etc.) to promote the market for this secondary raw material.
  - Main actors: waste managers.

  - In the field of energy recovery, ensure proper disposal of ash in various applications such as agriculture, forestry, cemeteries, concrete production, ceramics, and road infrastructure. Enhance the quality of ash through shredding, screening, removal of ferrous and nonferrous materials (using techniques like eddy current and over band separators), and chemical extraction of heavy metals. Operators (energy companies) can have a positive environmental impact by preserving virgin resources, substituting chemical nutrients, and saving money by avoiding landfilling.
  - Main actors: energy industries, farmers.
- Upcycling opportunities
  - Reuse wood waste such as furniture, timber and beams as new products by promoting repair centres. Such centres could also act as a place of exchange to encourage interaction between users and the reuse of wood products as furniture. Main actors: companies and households.

5.2.2. Potential Pathways and main actors

To identify potential pathways to market the secondary raw materials from wood waste and wood industries, it is necessary firstly a light description of the main actors involved in the value chain, specially in the wood waste management and treatment, as can be seen in the following figure [88].



Main value chain	Production	Feedstock provision	Suitable / processed products	Distribution	Post-processing	Valorisation	By-products
Supporting chain	Collectivities	Collecting sorting	Processing Refining	Storage and distribution equipments Handling	Processing Refining	Energy (electricity, heat, cold, syngas)	Undersize particles, ashes
	Industriies	Collecting sorting	Blending	Deal	Blending	Recycling : panel industry	
	Building Demolition Renovation	Collecting sorting		Transport		Re use	
Value chain actors		Waste companies	C&D	Transport companies	Industrial OEM	Energy operators	Cement works
		Building recyclers	Waste operators	Logistic companies		Panel industry	Waste treatment
		Brokers	Manufacters		Manufacters		Civil ingineenring (road infrasctructures)
			End users and subisdiaries				
			Engineering, research and development	Engineering, research and development	Engineering, research and development	Engineering, research and development	Engineering, research and development

Figure 21. Example of wood waste management value chain [88].

The life cycle of wood products in the forest industry flows through the various wood-based industries and is ultimately used in a final product, incinerated or landfilled. It should be noted that the forest-based industries in general cover a wide range of economic activities, including wood-based industries, the pulp and paper industry, as well as the printing industry. Roundwood material is the largest type of wood raw material and is mainly used in the wood-based industries which include sawn wood production, wood-based panels and other wood products such as furniture, joinery and carpentry materials, wood-based packaging and other wood articles.

Other important material flows refer mainly to waste created during forest industry processes or recovered waste streams. Firstly, these are wastes from industrial wood processing, which are solid by-products that are not modified by any artificial (e.g., chemical) process, such as sawdust, bark or industrial chips. Secondly, there is recovered paper, which includes collected paper and cardboard. Other feedstock streams are the covering of used wood products (recovered wood or post-consumer wood).

A general flow diagram on the wood waste system, created by the European Commission [90], is presented here, illustrating the directions of the flows and actors involved in the wood waste value chain and setting out a generic view of this waste stream and the industrial symbiosis that would be desirable.

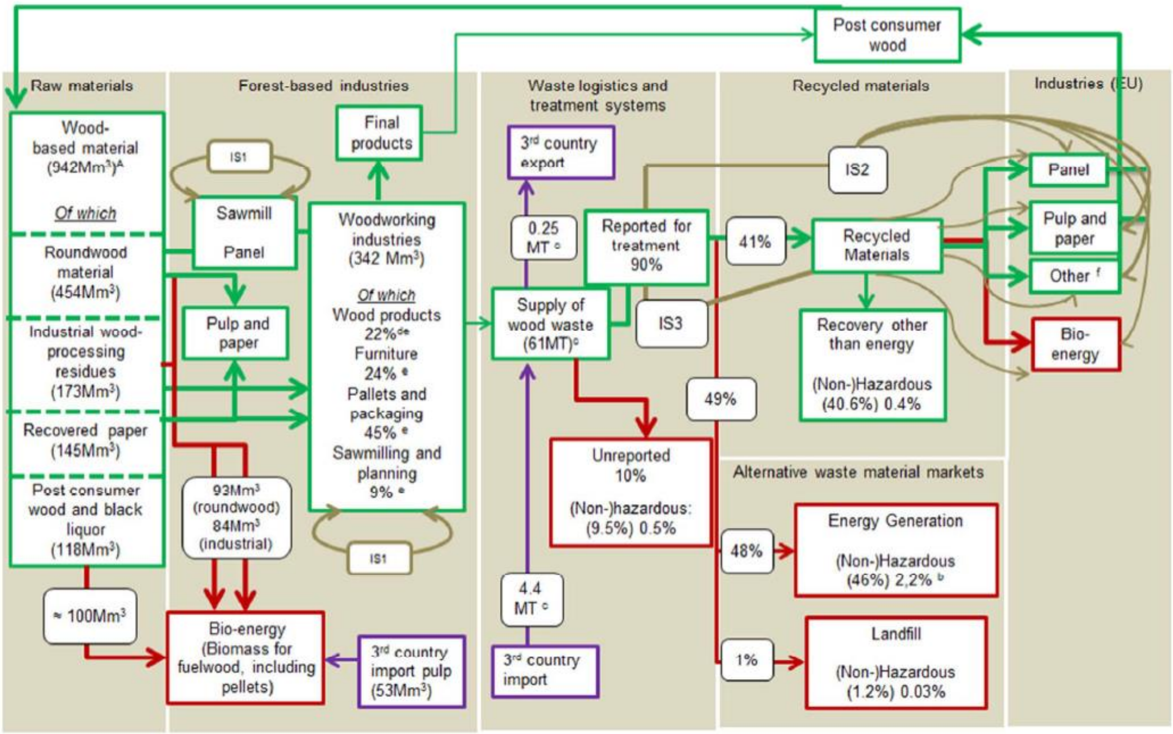


Figure 22. Wood waste flow scheme [90].

Source: Ecorys, Indufor (2013), Eurostat forestry statistics (2013), waste generation statistics (2010) and structural business units (2011).

Used colors: Green lines represent flows stimulating the circular economy, Red lines represent flows discouraging the circular economy. Purple lines represent trade flows. Brown lines indicate industrial symbiosis (type 2 and 3) exchanges. Note: the percentages reflect the share of the total supply of wood waste (61 Mt is 100%).

"**Biomass**" includes all woody by-products of forest managements, such as limbs, leaves, needles, tops and leaves.

Industrial symbiosis streams are not shown here in order to maintain a clear overview.

A: Indufor has calculated the use of all wood-based raw materials as roundwood equivalent (RWE, over bark) in order to make them comparable. The idea is similar to the tonnes of oil equivalent (toe) for energy but here done for the use of wood. For instance, the use of bio-energy is calculated as the use of wood in cubic metres (instead of e.g., toe; Joules) and the use of recovered paper is also calculated in cubic metres of roundwood, instead of tonnes.

B: Treatment of hazardous wood waste for energy generation includes incineration disposal (0.06 Mm3) and energy recovery
(1.28Mm3)

C: 2010 figure

D: The manufacture of products of wood, cork, straw and plaiting materials includes the production of veneer sheets and woodbased panels, assembled parquet floors, other builders' carpentry and joinery (such as roof frame elements, doors, windows, shutters and their frames, stairs, railings and prefabricated buildings), wooden containers, and other wooden products such as handles, clothes hangers, household utensils and kitchenware, as well as basket-ware and the production of fire logs and pellets..

E: 2011 figure and based on production value

F: E.g., animal bedding

Market in the wood industry is composed by thousands of mainly small and medium sized companies. Nevertheless, there are players with some market power, like large integrated companies (from forestry to production) and large integrated waste management companies (often with a dedicated public task or cross-border activities). These companies are also exposed to other, more global, market dynamics (trade and price shifts, global competition, etc.).

Within the study carried out in "Analysing of certain waste streams and the potential of industrial symbiosis to promote waste as a resource for EU industry" [90], a series of stakeholder interviews were conducted to gather information on industrial symbiosis networks in the wood industry, as there is limited public information available on the topic. The interviews revealed that most wood-based industries are involved in industrial symbiosis type 1 (IS1), where residues from wood production are typically used for internal heat and/or power generation within the factory or reused in the production of final products. The existence and potential of SI2 (direct exchange of materials between companies) varies between industries, while SI3 (exchange via a recycler or a raw material platform) is especially prominent in the wood sector.

No wood waste is produced in the sawmilling industry. Sawdust and bark are used directly in on-site pellet mills or sold to local pellet mills (IS2). Chips, the most valuable by-product, are sold to local board, pulp and pellet mills as well as to energy industries. If necessary, the industry uses its own production waste to generate energy (IS1) and does not use waste from external sources.

Producers in the panel industry reuse their own production residues in the manufacturing process of the final products or use them as biomass for energy generation. If the waste is not suitable for reuse (IS1) due to contamination, specialised incinerators collect and handle this contaminated waste in accordance with legislation. The panel industry buys waste wood directly from companies with large quantities of high-quality waste (IS2), together with virgin wood from the forestry and sawmill industries. This wood is used not only for production but also for heating purposes.

According to one of the studies referred [90], there are some industrial symbiosis potentials uses and overviews that can be addressed (Table 10).

Table 10. Overview of the potential for industrial symbiosis per wood industry [90].

Industry		Reuse (IS 1)		Direct exchange (IS 2)		Via recycler (IS 3)
Sawmill	Yes	Own residues as biomass forenergy generation.	Yes	Sawmills are sometimes integrated with a pulp, panel, pallet or energy plant with direct transfer of by-products.	Yes	Sawmills sell by-productsto the market (e.g., panel) through collectors.
Paper & Pulp		N.a.	Yes	(District) heat and steam delivered to nearby sawmills, pallet producers, and municipalities.		N.a.
Panel	Yes	Own residues used in final products or as biomass for energy generation, subject to legislation.	Yes (rarely)	Purchase in large quantities from individual companies.		N.a.
Pallets	Yes	Own residues as energy or heating in production process	Yes	Receives process steam from district heating plants, sawdust from sawmill[167]	Yes	Collected by 3rd party and delivered to panel industry
Packaging	Yes	Increasingly common for commercial reasons and to meet ISPM	Yes	Produce large amounts of high quality waste that can be sold directly to others	Yes	Collectors shred the wood and remove nails to make it sealable product

		15 regulation				
Furniture		N.a.	Yes	If large quantities of high quality wood waste is available		N.a.
Construction		N.a.	Yes	If large quantities of high quality wood waste is available		N.a.

N.a: No Applies.

The wood waste management system is based on the collaboration and fulfilment of responsibilities of several key actors who play a crucial role in ensuring the efficient handling and sustainable management of this waste stream. The actors involved belong to different sectors, each contributing with their responsibilities and actions to the challenges and opportunities of the transition towards a more circular economy.

Taking into account all the information exposed in this section, several potential pathways can be identified from this literature review, that could suppose an initial stage to develop policies and action plans to improve the efficiency of wood secondary raw materials market, foster the interaction among stakeholders involve in value chain and encouraging the valorization and reuse of this flow.

- Creation of new platforms and systems that enable live information exchange, providing data on potential needs for secondary wood raw materials and their location. In this sense, most of the actors involved in the value chain (Figure 21) should be connected and participate in such initiatives to create a constantly updated environment.

  Main actors: digital developers, wood waste producers, waste managers.
- New public administration policies to encourage the reuse and recycling of wood residues and secondary raw wood materials, with particular emphasis on improving sorting at the producer site, thus encouraging faster recirculation of extracted secondary raw materials.

  Main actors: Public administration.
- The presence of industrial actors in each region or country, with competences to valorize wood waste, is essential to foster a real market for wood-based materials. It is therefore necessary to facilitate the start-up of new SMEs and companies in this sector by ensuring a line of investment and easy bureaucratic procedures.

  Main actors: wood industrials, wood waste managers.
- Promote the reuse of wood waste, including furniture, timber, and beams, by establishing repair centers. These centers would serve as hubs for exchanging and refurbishing wood products, fostering interactions among users and encouraging the reuse of wood materials in furniture production. Municipalities must provide the sites to integrate these centers into the circular economy strategy.

  Main actors: Public administrations, households.

5.3. Resins

5.3.1. Recycling/Reuse and upcycling opportunities

Overall, resins play a crucial role in various industries, offering a wide range of benefits that enhance product performance, durability, and efficiency. Their versatility and diverse properties make them indispensable in modern manufacturing, construction, electronics, automotive, and many other sectors. Key advantages of resins are their adhesive properties, coating and protective properties that enhance durability, water resistance and chemical resistance, high strength and tuneable properties, moldability, insulating properties and UV stability. Figure 23 shows the variety of products that contain phenol-formaldehyde resins – this is much broader when including other type of resins such as epoxies, alkyds, etc.

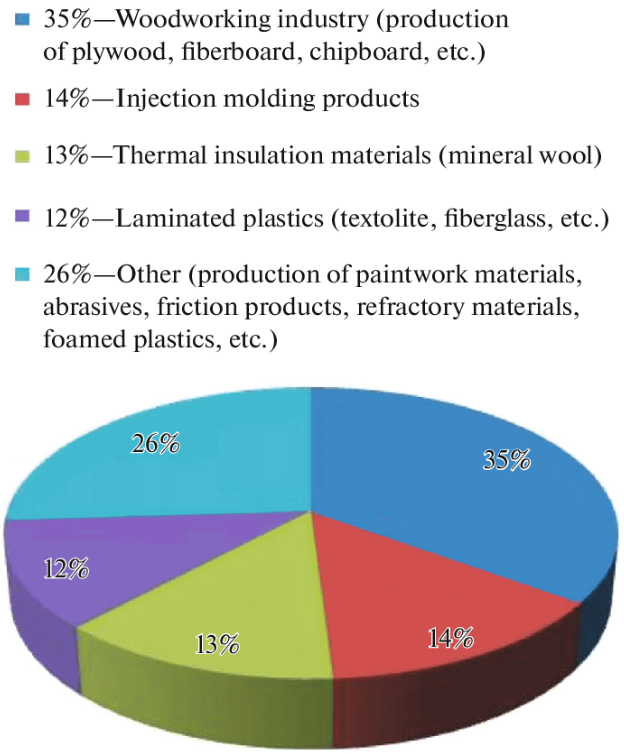


Figure 23. Applications of phenol-formaldehyde resins [91].

Despite the many benefits, conventional resins such as formaldehyde-based resins used in wood panels constitute a concern in terms of sustainability. For instance, they tend to be *i)* fully petro-based, with a production process that involve toxic compounds and has high energy requirements; *ii)* known to release formaldehyde over time, which is toxic to humans and the environment; *iii)* non-biodegradable in natural conditions; *iv)* not easily recyclable due to the crosslinked structure; *v)* difficult to separate from the typically multimaterial end product; *vi)* polluting when landfilled or incinerated.

New circular schemes and ongoing research and technological advancements aim to mitigate these drawbacks and improve the overall sustainability of resin-based products and applications. Some key opportunities are listed below:

- Reuse**.** The durability of products containing resin is an advantage that allows for a long lifespan of said products, particularly when well maintained. Resin-containing materials can be repurposed in other applications, e.g., wood panels can be reused to build furniture, decorative items, or even as reclaimed wood back in construction. The main challenge when addressing the repurpose of (almost any kind) of waste is adequate collection and sorting. There is a need for supply chain platforms and networks that enable the flow of secondary streams, as well as harmonized standards, certification schemes and sorting technologies to validate and standardize said streams. These points are fundamental for the establishment of new circular value chains.
- Mechanical recycling. The outstanding performance of conventional resins, arising from their covalently crosslinked networks, has the limited recyclability as a drawback. Some resin-containing products can be mechanically recycled by means of cutting and grinding, homogenizing the obtained particles, and using them as fillers in new thermosets and thermoplastic materials [92]. For example, wood panels can be grinded and recycled into particleboards and other wood-based products. While mechanical recycling helps reduce waste

and promote the sustainable use of resources, proportions of fillers in new materials vary depending on the application requirements (notably, mechanical properties tend to worsen), being typically in the range of <10-20wt%. In an example, 20% of re-grinded PF resin was incorporated into a virgin phenolic molding compound, and using the recycled thermoset material as filler provided a perfect adhesion band for the virgin material [93]. Another study demonstrated the successful reactive injection of pulverized recycled resin (max 20%) with virgin PF to make new resins, where good properties were achieved [94]. Through advanced processing such as the “push-pultrusion” process, new composite products based on reused composites can be obtained in a continuous, industrial manner, and using up to 70% by weight of recycled composite, with 30% virgin material [95]. Despite the possibilities, large scale mechanical recycling of resin-containing materials is still limited. Because of the challenges associated (energy-intensive, low re-introduction of recycled materials back into the loop, non-meltability of resins, heterogeneity of resin-containing composites, etc.), the recycling rate of resins has historically been relatively low. Instead, they are often disposed of through waste-to-energy processes or in landfills. This panorama is expected to change with the new regulations being set by the EU (see Section 4.3.2.) and with the development of new recycling technologies and new types of resins (see below).

- Thermal recycling. Thermal recycling can be categorized into aerobic and anaerobic combustion, with the latter often referred to as pyrolysis. The presence of oxygen plays a crucial role in determining the recycling outcome. Aerobic thermal treatment, such as incineration, primarily focuses on energy recovery but does not involve material recovery. As a result, it is not classified as recycling. Nonetheless, this is one of the few commercial solutions for avoiding the landfilling of complex composites such as Glass Fiber Reinforced Polymers (GFRPs). For instance, scrap GFRPs are used as feedstock for cement processing in cement kilns. In this process, the matrix material is converted into gas and energy, while the glass, primarily composed of borosilicate and calcium carbonate, is used as a resource material for cement clinker. The resulting cement clinker is later ground to produce cement. The European Composites Industry Association recommends recycling GFRP thermosets through this method, as it is currently the only technically and economically feasible alternative to landfilling.

Another possibility is to perform pyrolysis, a solvent-free process where high temperatures (300 - 800 ^{o}C) are applied to the material at an anaerobic atmosphere, leading to the production of a liquid product (so-called “pyrolysis oil”), gaseous products and solid, carbonaceous products. The yield of each fraction will be largely dependent on the pyrolysis conditions applied (residence time, temperature, heating/cooling ramp), to the use (or not) of catalysts, as well as on the particle size and chemical composition of the resin. The products can be use as feedstock for the manufacture of new materials, and as a source of chemical building blocks and high value energy carriers. From a circular economy perspective, pyrolysis is regarded as the most advantageous industrially available thermal recycling treatment presently. Nevertheless, while industrial pyrolysis processes are undergoing development, their economic viability remains uncertain. Ongoing investigations address aspects like reducing pollutant emissions, optimizing the required process energy and developing value chains and new products from the streams obtained by pyrolysis.

- Chemical recycling. The chemical recycling of resins is still in the early stages of development and is not yet widely implemented on a large scale. Nonetheless, this route is very promising as a potential solution to address the challenges of recycling thermosets. It involves breaking down their cross-linked structure into the original monomers or other valuable chemical feedstocks, which can be used to produce new materials or other products, Chemical recycling (often referred to as solvolysis) can be performed by applying various conditions, solvents and catalysts to the resin, which will depend on its chemical structure and the targeted products. Several investigations exist in scientific literature targeting the recycling of various resins and composites. For formaldehyde resins, for example, acid hydrolysis of UF resins is shown to recover a formaldehyde solution that can be used in new resins [96]; the alkaline and acid hydrolysis of MF resins also generates building blocks for new resins [97,98]; the conversion of PF resin wastes to carbonaceous solids is possible by a catalyst-free process using supercritical methanol [99]. Chemical recycling approaches are carried out at milder conditions than thermal recycling approaches, and the use of catalysts and specific reagents typically lead to a controlled depolymerization of the resin. While this can be advantageous from the point of view of obtaining valuable chemicals and getting closer to the desired “closed-loop”, the commercial-scale implementation of these technologies is limited. Accordingly, several factors contribute to this:

- Technological Maturity. Developing efficient and cost-effective chemical recycling methods for conventional resins is a complex task that requires significant research and development and is not yet mature.
- Economics. The economics of chemical recycling processes need to be competitive with virgin resin production and existing waste management practices for resins. This goes hand in hand with obtaining valuable products from recycling processes rather than energy carriers or fillers, which have a very low value and cannot justify the energy and chemical usage of the recycling process.
- Market Demand. There must be a market demand for the recycled products derived from resins to drive investment in chemical recycling technologies.
- Regulatory Environment. Supportive regulatory frameworks and policies can encourage the development and adoption of chemical recycling technologies.
- Environmental Impact. The frequent use of hazardous solvents and strong acids or bases often results in questionable life cycle analysis and environmental impacts.

While the chemical recycling of resins is not yet widespread on a large scale, ongoing research, technological advancements, and increasing awareness of sustainability and circular economy principles are driving progress in this field. As these technologies mature, they may become more economically viable, energy efficient, and contribute to more sustainable waste management practices for resins. The status of resins recycling can be illustrated by Figure 24. Accordingly, conventional resins are a result of the crosslinking of two main monomers, with added fillers and/or additives. Besides the widely practiced incineration for energy production and undesired/forbidden landfilling practices leading to pollution, current thermal and chemical recycling technologies are not mature enough to enable a recycle/upcycle, leading mostly to the downcycling of the material into low value fillers and complex chemical mixtures that often need upgrading and purification steps to be used as energy source and source of molecular building blocks.

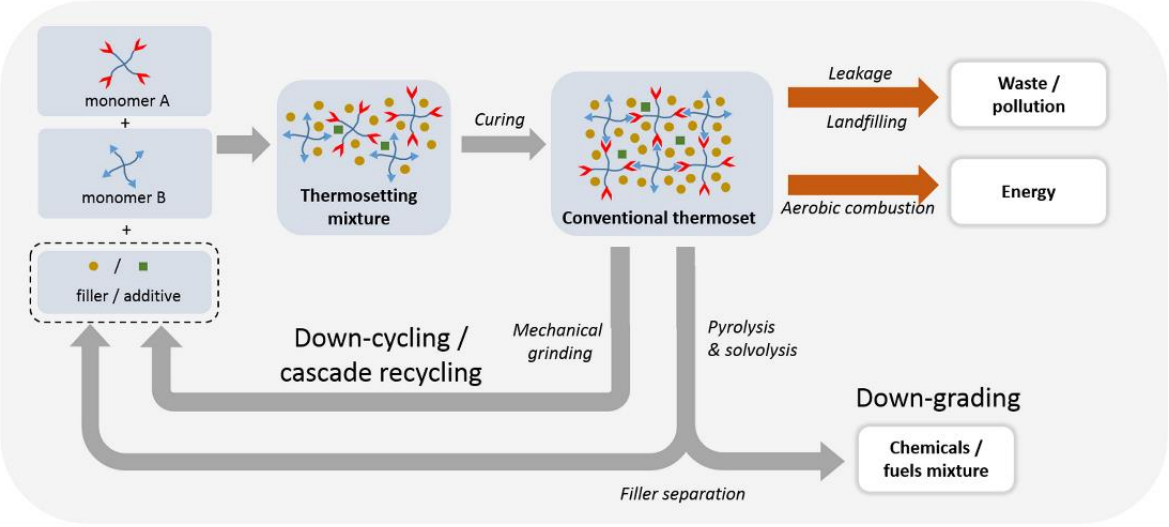


Figure 24. Schematic overview of conventional thermoset waste processing and recycling routes **[100]**.

- Biological recycling. Notably less explored than chemical recycling, during biological recycling microorganisms such as bacteria, fungi, and other decomposers feed on organic matter, breaking it down into simpler substances. This process occurs in nature and is also harnessed for waste management and environmental sustainability purposes. While resins are considered non-biodegradable, advances in research were able to identify possible robust microorganisms able to break down some of their structures. For instance, three independent lines of evidence established the biodegradability of PF resins with the white-rot fungus *Phanerochaete chrysosporium* [101]. White-rot fungi are known for their ability to degrade various organic pollutants, including phenolic compounds. They have a unique enzymatic system capable of breaking down complex organic molecules by oxidative pathways. When exposed to phenolic compounds, white-rot fungi produce said enzymes that attack the aromatic rings of the phenols, leading to their transformation into smaller, less toxic molecules that are further metabolized by the fungi or incorporated into the fungal biomass.

The ability of white-rot fungi to degrade phenolic compounds has significant implications for bioremediation, considering that a large portion of chemicals and materials (including resins) consist of phenolic building blocks (such as PF resins, epoxies and polycarbonates, largely produced from BPA). Thus, these fungi have been studied and applied in various biotechnological applications for the removal of phenols and could possibly be a route for the biological recycling of phenolic resins. More research is necessary to better understand the mechanisms and controlling factors before it can be widely applied and commercially available, and main challenges refer to the scalability and viability of industrializing such route, as the timeframe of biological processes is much slower, as well as the update of organic matter by the microorganisms.

- Novel resin formulations. The above sessions addressed recycling possibilities (both conventional and innovative) for the valorization of wastes containing conventional resins, particularly formaldehyde resins. Another perspective can be applied to this topic, which is tightly connected with EU regulations on toxic-free chemistry and eco-design and refers to the development of novel resin formulations with easier recyclability, biodegradability, and lower to no fossil-based building blocks. On this note, extensive research is looking into these replacing phenol and formaldehyde with biobased alternatives [102]. One of the obvious potential substitutes for phenol is lignin, one of the main components in lignocellulosic biomass and most available natural source of phenolics. For instance, pyrolysis oils from lignin have been successfully implemented at up to 50wt% replacement of phenol in PF resins to produce plywood and OSB boards commercially, but costs are usually higher [103–105]. Another nature-made option are tannins, a diverse group of naturally occurring phenolic polyesters found in various plants, especially in fruits, nuts, seeds, leaves, and tree barks. So far, tannins are the best direct replacement for phenol in resin preparation, but they are limited by a weak adhesiveness, high viscosity and lack of intermolecular crosslinking. Furthermore, the availability of tannins is limited, and costs tend to be higher compared with fossil building blocks. Tannin adhesives (mixed with UF) for particleboard were produced commercially [104,106]. Cardanol (a byproduct of the cashew nut processing industry), gallic acid, different types of bio-oils have been also investigated as ways to improve the overall sustainability of resin formulations [107,108].

Formaldehyde, one of the most important chemical building blocks in the resins sector and a chemical of high concern in terms of safety, can be substituted for alternative raw materials from biobased sources. The major challenge in replacing formaldehyde is finding an alternative with a high reactivity and low molecular weight. hydroxymethylfurfural (HMF), furfural, terephthalaldehyde, and glyoxal have all been reported as potential replacements for formaldehyde in the production of resins [107,109].

Among possible advances in resin formulation using biobased building blocks, adhesives from proteins are a notably sustainable solution to address indoor air quality and formaldehyde exposure concerns. These adhesives utilize renewable and readily, largely available secondary raw materials. Importantly, protein-based adhesives do not compete with human or animal nutrition; rather, they originate as by-products from related industries. Despite these benefits, protein-based adhesives encounter certain drawbacks that currently limit their industrial usage. For instance, hydroxyl group-rich materials exhibit poor water resistance, and long molecule chain polymers can pose challenges related to viscosity. For example, some types of soy proteins are used commercially, however, current soy-based adhesives are not 100% natural. They still use conventional chemicals to provide a firm binding and thus are not biodegradable or easily recyclable [110,111]. To overcome these limitations, the development of an environmentally friendly wood adhesive system that effectively competes with UF and PF resins in terms of price and performance is needed. The Greek demonstrator of the DigInTrace project will target this route by extracting proteins from oilseed cakes, an agroindustry byproduct, and valorizing said proteins by replacing phenol with them in PF resins that will be subsequently used in the production of wood panels.

As aforementioned, the replacement of conventional fossil-based building blocks with biobased alternatives can bring several benefits in terms of safety, biodegradability and overall sustainability. Furthermore, there is a substantial demand for innovative polymer architectures that enable low-energy molecular debonding for easy matrix removal or recycling. This molecular debonding can be achieved through two main approaches: stimuli-triggered degradation or the introduction of dynamic covalent bonds into the networks.

Stimuli-triggered degradation entails modifying the conventional cross-linked resin by incorporating labile bonds that facilitate downstream chemical recycling processes, for example at milder conditions. Although the recycling pathways through stimuli-triggered degradation can enhance resins circularity, they nonetheless result in the destruction of the original polymer architecture (similar as in the current case of pyrolysis and solvolysis), and the products find use in applications with lower performance (i.e., down-cycling). On the other hand, dynamic covalent chemistry provides an alternative recycling approach for crosslinked polymers while preserving the overall polymer structure. These polymers often possess damage-healing capabilities or can be reprocessed before recycling. Dynamic covalent bonds are typically triggered by various stimuli like thermal, pH, light, or moisture. Reported covalent chemistries include C-C, C-N, C-O, disulfide, and boron-oxygen bonds.

Figure 25 below illustrates the circularity of thermoset materials with inherent recyclability. One can envision that an ideal resin system would combine biobased building blocks with dynamic covalent chemistry (associative and dissociative crosslinks), thus avoiding fossil-based, often toxic building blocks, valorizing non-edible, largely available biomass (ideally agro-industrial residues) and enabling fully circular value chains where crosslinked polymeric matrixes (such as in resins) can be activated and reprocessed in a controlled manner into new materials with similar properties and performance. Significant research developments are needed to achieve a high technological maturity and efficient production processes, also taking into consideration the full life cycle and impacts of producing and reprocessing this new family of innovative resins. Furthermore, regulations must be further tightened to facilitate the introduction of non *drop-in* solutions into the market and increase the viability and support of advanced materials that currently cannot compete with the low prices of fossil-based chemical building blocks.

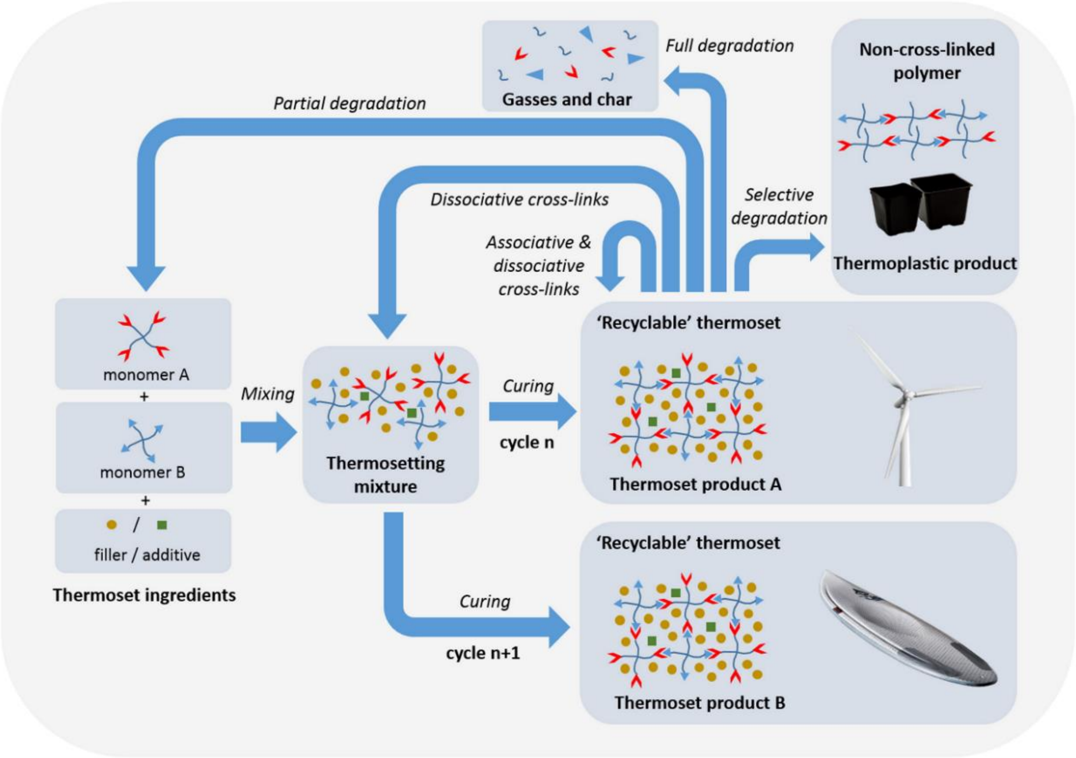


Figure 25. Schematic overview of the circularity of thermoset materials with inherent recyclability [100].

5.3.2. Potential Pathways and main actors

As seen in the previous sections, the resins sector is very diverse in terms of types of resins and final applications. While highly industrialized and standardized in EU, such markets variability' and the difficulty to recover pure resins and properly recycle them constitute major challenges for closing the loop and avoiding landfilling and incineration. Nonetheless, technology has been advancing towards novel efficient solutions, and regulations are increasingly promoting circular value chains and restricting the use of chemical building blocks of concern and fossil-based formulations responsible for substantial CO_2 emissions during manufacturing and with problematic end-of-life due to non-biodegradability.

The current scenario is illustrated in Figure 26 below. The two possible sources of building blocks, petro-based and biobased, are depicted, where conventional resins are largely derived from the former. Besides conventional resins, novel advanced resins (reprocessable, self-healing) and biobased resins are considered, since these pathways are under constant development and in some cases, options already exist commercially (e.g., partially biobased resins). The blocks marked with a red triangle (△) highlight steps in the value chain that are not yet fully established in a large scale and/or in early stages of development.

The most common process, which is still performed with a very low proportion of end-of-life materials (as they are mostly incinerated) remains the mechanical recycling. In this route, the waste is simply reduced in size, with little to no sorting, and the resulting stream is re-introduced in the same value chain (e.g., wood panels) or others (e.g., construction materials such as concrete) as a filler or low value additive. Notably, advances in terms of separation and sorting will lead to better secondary streams, allowing for *i)* higher incorporation percentages in materials, *ii)* suitability to be used in other composites of higher value, diversifying the applications and increasing the feasibility of recycling, *iii)* a purer and more homogeneous stream to be upgraded via other recycling strategies, e.g., thermal and chemical.

Thermal recycling, notably pyrolysis, is a relatively well-explored route to produce solids (pyrolytic carbon) that can be also used as fillers as well as potentially valuable liquid streams (pyrolysis oils). Nonetheless, value chains able to utilize said liquids *as-is*, or their upgrading and separation/purification into value chemical building blocks is still under development and did not reach feasibility for upscaling. A potential pathway involves the co-feeding of pyrolysis oils in current refineries, nonetheless, the requirements are challenging to meet depending on the resin, such as the low oxygen/nitrogen/sulphur levels, low-to-no acidity, no ashes, no char formation, etc.

Several chemical recycling routes are also under investigation to enable the recovery of valuable chemical building blocks, but feasibility is so far hindered by downstream processing needs (e.g., separation and purification of complex mixtures, which are typically energy-intensive) and by the conditions, solvents and catalysts usually needed for chemical recycling. In this context, the development of innovative reprocessable resins that can be partially depolymerized in a controlled manner by breaking specific chemical handles (via stimulus such as temperature, change of pH, etc) is an exciting development in the field. Accordingly, said resins can be more easily separated from other materials and repolymerized in a reversible manner, facilitating their recycling with little to no performance loss in the same application, extending their lifetime and effectively closing the loop. This development is not yet in a commercial stage though.

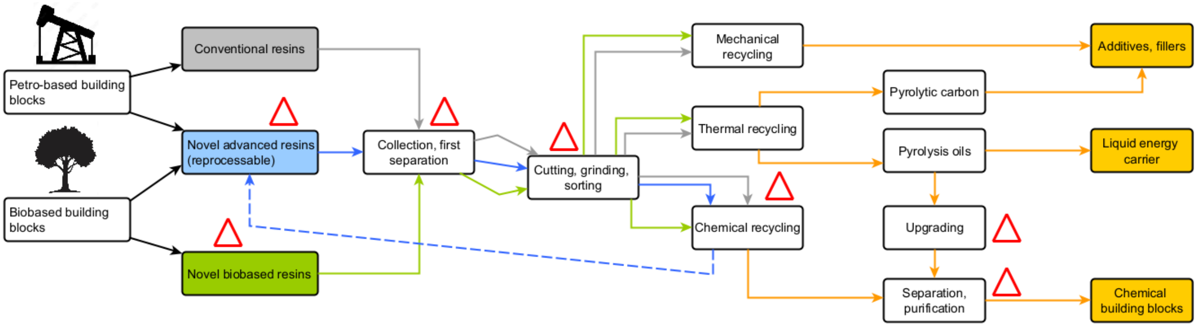


Figure 26. Possible pathways within the resins sector, with underdeveloped steps marked with a △ .

In this scenario, the following main actors can be highlighted:

- Resin Manufacturers and Waste Stream Collectors. The development of robust, resilient circular value chains is highly dependent on the proper collection and first screening of materials. This is a typically overlooked primary step that involves a well-organized supply chain with low volatility in the stream's volumes, prices and quality. Furthermore, depending on the distances between collection and recycling points, recycling might not be feasible. Therefore, a case-by-case study is needed for the supply chain, and depending on the envisioned feedstocks and products, decentralized units are favoured to decrease the transportation costs and environmental impacts. Therefore, a network of collectors dedicated to multimaterials containing resins (e.g., wood panels and composites) is of paramount importance. The development of this early stage brings, besides the waste valorization benefits, regional benefits, as it creates jobs and strengthens local economies.

This activity is positively affected by the EPR (extended producer responsibility) concept. In the EU, EPR is a fundamental principle applied to various products, placing responsibility on the producers to take environmental considerations into account throughout the entire life cycle of their products, including their end-of-life stage. Regarding resins, the resin manufacturer may have certain responsibilities depending on the specific product and its use. In such cases, requirements exist to participate in waste collection, recycling, or recovery programs to ensure proper treatment of the product at its end of life. Importantly, the implementation of EPR principles can vary from country to country within the EU, as well at the national or regional level. It is essential for resin manufacturers to be aware of their obligations and work collaboratively with other stakeholders to ensure the sustainable management of products throughout their life cycle. Furthermore, it is essential for policymakers and governmental actors to strengthen EPR locally and ensure the participation and responsibility of relevant stakeholders in the waste valorisation processes.

- Waste Pretreaters – Separation and Conditioning of Waste Streams. The recycling of current commercial resins is not trivial due to its non-meltability and the multimaterial character of end products. In this sense, and like many other sectors with similar challenges, the development of efficient separation, cutting, grinding and sorting techniques is fundamental for the feasibility of the recycling processes and for obtaining high quality products from waste streams valorization. There are several types of waste sorting methods, and they can vary depending on the level of detail and the specific infrastructure available. Some types of waste sorting technologies include i) advanced mechanical systems such as conveyors, screens, magnets, air tables and optical sensors used to mechanically sort materials based on their physical properties; ii) automated, high-tech sorting systems that use new sensors, artificial intelligence and robotics to automatically identify and separate different types of waste materials. Accordingly, an effective waste sorting is essential for maximizing resource recovery, reducing landfill waste, and promoting sustainable waste management practices. As such, actors in this stage are extremely important to guarantee that the collected waste is separated in valuable streams in the most efficient way. This will subsequently support and justify the development of advanced recycling processes to close the loop, obtain valuable products from secondary streams and establish resilient supply chains based in said streams.
- Waste Recyclers and Technology Developers. The development of advanced recycling technologies is fundamental to obtain high value products that compensate extra processing steps (and their energy, chemicals, and water costs) and are overall advantageous in terms of sustainability and efficiency. Said technologies are still immature for various waste types, notably thermosets and multimaterials (such as resins), and actors in the fields of R&D, engineering, prototyping and upscaling are thus fundamental to push forward new circular value chains. The development of new resin formulations aligned with eco-design and sustainable chemistry principles is also highly advantageous to facilitate the recycling and avoid associated emissions and handling of concerning chemical building blocks. Furthermore, “end users”, e.g., resin manufacturers and other stakeholders interested in upgraded waste streams such as refineries and other chemical industries, must be involved in said developments since early stages in order to validate and/or co-develop the technologies, as well as provide specific inputs on the requirements for each envisioned application.
- Standardization and Certification Bodies. The development of new specific standards and certification schemes will be important to achieve stable and uniform streams of secondary raw materials and their upgraded products. For instance, the variability on the volumes, properties and often lack of information on the origin and composition of waste streams is a major challenge for the development of new processes and products, and traceability is increasingly sought by stakeholders and consumers. While technical standards are well established for virgin resins and their products, it is necessary to extend these to recycled products to ensure their sustainability and safety.
- Governmental Authorities and Policymakers. The development of disruptive technologies and new business models requires strong commitment from all perspectives: industrial, civil, academic and governmental. In the context of recycling, regulations and policy are determinant to break unsustainable practices, promote innovation, ensure that responsibility is given to stakeholders along the full value chain, and ensure a proper end of life of materials with safety and sustainability as core aspects. Furthermore, support to de-risk innovative technologies via funding instruments and subsidies are often needed. Finally, initiatives that communicate, educate and engage the civil society are very important to promote sustainable practices in all spheres and ensure that new technologies and value chains are sustainable also from the point of view of creating opportunities, socio-economic development and wellbeing to communities.

5.4. WEEE Plastics

5.4.1. Recycling/Reuse and upcycling opportunities

As seen above, WEEE recycling faces major challenges, such as the large mix of different materials, often containing hazardous substances, but nevertheless, WEEE recycling holds many opportunities to reduce environmental impacts as well as to generate economic value. It was estimated that WEEEP alone, which typically accounts for 15-30% of total WEEE by weight, had a potential raw material value of 15.043 million euros in 2016 [58].

It is indisputable that as with many other materials, especially those containing hazardous substances, plastics from WEEE present aspects that either directly or indirectly hinder their recycling/reuse. Among the most significant of these are:

- Mixing of materials: After separating the plastic fraction from the rest of the materials that make up WEEE, a very complex mixture of plastics remains, which may consist of more than 15 different types of polymers, and a variety of additives, including harmful and restricted substances such as brominated flame retardants (BFRs) [55,112]. These therefore need to be removed during the recycling process. Even so, the resulting mixture of plastics may need to be further separated in order to obtain a reasonable quality of SRM, which makes the process even more complex. Given the complexity arising from this mix of plastics and the limitations of existing technologies for proper sorting, it is estimated that around 40-50% of the plastics captured in WEEE are not recycled as well as they could be [53,55].
- Recycling complexity: Although WEEE collection rates are relatively good, this is largely due to the easy recovery of certain materials, especially metals [113]. However, for more difficult materials such as plastics, the results and recycling rates are much worse [113]. This is mainly due to the fact that the process requires many steps, such as shredding, separation by sinking and flotation, washing, drying and compounding, i.e. a lot of infrastructure, which together with the expected logistical complexities, makes new recycling plants for these materials economically problematic, resulting in many cases in the recycling of plastics going unattended [58,113].
- Low target volumes: As a consequence of end-of-life products focusing on specific components, this results in a low-volume waste stream compared to post-shredding recycling[58]. In addition, the recycling process is influenced by possible fluctuations in the quality or quantity of the input waste, leading to the risk that consistent volumes or quality of recycled plastic cannot be produced [58].
- Economic issues of recycled plastics: The fact that the price of recycled plastics is lower than that of conventional plastics is a major driver for the former, but since the value of the latter is highly correlated to the value of oil and this can vary relatively easily means that the economic viability of the recycling operation is dependent on the market value together with the cost of processing [58].
- Quality requirements: In order for plastics from recycling to be used in new components, a number of quality requirements must be met (mechanical, chemical or thermal properties, material behaviour during processing, ageing behaviour and aesthetic appearance of the plastic surface, etc.). These will generally be defined by the producers themselves and would also depend on the intended end use. As a consequence of its previous use and the processes undergone, the material may be degraded and it becomes necessary during the recycling process, in case the quality is to be maintained, to carry out certain actions in order to reduce deterioration and improve the material [58].

But despite all this, thanks to multiple aspects such as the ability to recover high quality recycled plastics, the diversity of alternatives for sorting, the increasing demand for plastics, the favourable environment created by the European Commission's strategy for plastics in a circular economy and the existence in some European countries of landfill bans requiring the incineration or recycling of plastics, there is interest in promoting the recycling/reuse of these materials [58]This focus on re-use is due to the contribution of this strategy to the reduction of waste generation and resource conservation, as well as to energy savings, as the higher electricity consumption of older equipment is more than compensated by lower energy consumption for the production and manufacturing of WEEE products [114].

However, the option of re-use could be ignored, as Member States and stakeholders can achieve the targets by favouring recycling over preparing for re-use. Preparedness for re-use currently faces a number of obstacles that hinder its viability, such as a high dependency on product design, lack of adequate logistics, resistance from producers, consumer perception of re-use, the legislative framework (no specific target for preparedness for re-use) etc [115].

For all these reasons, recycling, especially mechanical recycling, is the most widely used strategy due to its simplicity and lower cost [116].

Through these types of opportunities, within the scope of the WEEE plastics recycling process, the following options have been identified that can be used, as appropriate, to improve the process:

Manual sorting at the source

It is true that if a company processes large quantities of inputs on a regular basis, manual sorting may not be sufficient to meet demand, in addition to the need for skilled workers and the possibility of human error. However, there is the possibility of combining it with automated processes, if access to the necessary funding is available, which results in an increase in the efficiency of the e-waste plastics recycling process, as it is essential to sort parts such as cathode ray tubes and flat panel display plastics to avoid large-scale dispersion of regulated waste, e.g. plastics containing BFRs in the recycled raw materials [117,118].

Up-front dismantling-based recycling of plastic components [58,71]

At present and as discussed above, mechanical recycling is the main method for the recycling of plastics from WEEE, basically consisting of a size reduction of WEEE with shredding and subsequent separation of the materials into small pieces.

As with other materials (e.g., PWBs, cables), the possibility of focusing on specific end-of-life products and treating them by up-front dismantling of large and high-value plastic components prior to shredding has emerged to complement the current state of WEEE plastics recycling.

Within this possibility there are a number of strategies, which can be included in an existing infrastructure of a commercial post-shredder separation recycling facility:

- Dismantling based recycling of plastics for direct reapplication processes: In this case, the sorted plastics are individually processed to produce granulates that can in turn be used to generate high-quality products through injection moulding.
- Dismantling based recycling of plastics for masterbatch carriers: This strategy focuses on the recovery of FRs present in the plastics to combine them with virgin FRs to create FR-rich granulates, called MBs, which can then be added in injection moulding to FR-free granulates to create FR components.
- Blending with post-shredder plastic recyclates: With this option, during compounding, plastics resulting from the recycling of the dismantling process are mixed with those that have been separated after shredding in order to improve their quality.

Spectroscopic techniques with contact measurements [71,117]

For post-shredder mixtures, optical sorters capable of separating plastics by characteristics such as colour and type have become very popular thanks to recent developments in spectroscopic techniques. Among these, those with contact measurement stand out as they significantly improve the quality of the spectra used for identification. These sorting techniques are more effective when applied to a mixture made up of large fractions rather than to small fractions. Many of the following techniques are only available as benchtop systems or rugged handheld scanners suitable for on-site measurements, but can be used to identify plastic type and FR at component level in a disassembly-based recycling scenario:

- Fourier Transform InfraRed (FTIR) spectroscopy measures the response of plastics to infrared light. In this case the mid-infrared range is used, which also allows the identification of black plastics and in summary can discriminate most of the relevant WEEE plastics.
- Raman spectroscopy operates on the principle of the Raman effect and provides similar spectra to FTIR and is often used as a complementary spectroscopy as it is more sensitive to certain C bonds, while FTIR is more sensitive to the detection of OH bonds.
- X-Ray Transmission (XRT) analyses the degree to which X-rays are absorbed by a material and determines the atomic density, which allows differentiation between FR and non-FR plastics, but as a consequence of overlapping densities, it is not able to distinguish between Br and P-based FRs.
- X-Ray Fluorescence (XRF) uses X-rays to create a characteristic fluorescence light response to identify the various elements present, such as Br. However, detection of the specific molecule from specific XRF is not possible.
- Sliding Spark Spectroscopy (SSSP) vaporises through a high-voltage spark a small part of the plastic surface, which emits radiation that can be measured to differentiate between Br- and P-based FRs.
- Laser Induced Breakdown Spectroscopy (LIBS) uses a high-energy pulsed laser beam to form a plasma that vaporises a small amount of the material's surface. In this way, the light emitted by the excited atoms can be used to identify the elements present in the material. This technique has been used to identify various types of plastics, to detect the presence of Br in them, and to distinguish between Br and phosphate FRs.

Dehalogenation / Extraction of BFRs [116,117]

Due to the presence of a number of hazardous substances such as BFRs, there are fractions that cannot be recycled. However, preventing these fractions from ending up in landfills or being incinerated, and avoiding the generation of corrosive brominated gases and dioxins.

- Pyrolysis in two stages to remove halogens before the decomposition of plastics.
- Low temperature (<250 ºC) catalytic depolymerisation technology that can process all types of plastics without the formation of dioxins and convert them into diesel fuel for energy.
- Hydrothermal treatment using supercritical water.
- Catalytic cracking to remove halogens during a pyrolysis process.
- Carrying out pyrolysis and treating the gas phase or the liquid phase by catalytic hydrohalogenation to transform the halogenated compounds into easily recoverable inorganic compounds.

Given the major problem posed by BFRs, which are very common in WEEE plastics, the development of techniques to extract them from the plastic fractions containing them has become very promising. For this purpose, there are chemical or solvent treatments, such as the following: which fulfil this function:

- Supercritical-fluid extraction (SFE); In this case, CO2 is brought to its supercritical state (temperature above 31.3 C and pressure above 7.28 MPa), and then introduced into a reactor containing the BFR-containing residues, which can be recovered after condensation in a separator.

- Pressurized liquid extraction (PLE) also known as accelerated solvent extraction or pressurised fluid extraction, is a method of extracting BFR using conventional solvents at high temperature and pressure.
- Microwave-assisted extraction (MAE) uses microwave energy to accelerate solid-liquid extraction solid-liquid extraction by thoroughly heating the solid sample and solvent.
- Solvent extraction is used to remove TBBPA in plastics from WEEE prior to pyrolysis. After extraction, the solvent can be purified, recycled and reused for other applications.
- Hydrothemal treatment; This process is regarded as one of the alternative technologies for recycling BFR-laden plastics, and it can also remove bromine from oil.
- Dissolution technique followed by precipitation of Liquid / Liquid extraction. This method has already been applied at a semi-industrial level (Creasolv), which has made it one of the most promising processes at present. The process involves the extraction of BFRs from e-waste polymers by a combination of solvents, followed by precipitation of the polymers from the solution. The BFR and other contaminant species can be extracted and remain in the mixture of solvent and non-solvent during the precipitation process, while the precipitated BFR-free polymer is then processed further by extrusion. The organic solvents used can be recycled, which leads to a reduction of the solvent volume compared to the volume of materials. Once processed and dried, the polymer has good mechanical properties and is compatible with RoHS.

Other opportunities of improvement

The recycling of WEEE plastics can be improved in many ways and from many perspectives, a number of recommendations and future opportunities are listed below with this objective in mind:

- Micro-factories [117]: Decentralise manufacturing through microfactories, making the technology more lean, agile and customisable, while reshaping and transforming e-waste plastics into a new, higher value product, rather than converting it into a plastic product.
- Improve the communication between pre-processors and recyclers: Better communication between pre-processors and recyclers would allow the former to know the particle size range needed, they could work in narrower ranges, which would result in a reduction of transport costs and therefore CO2 emissions.
- Sort brominated fractions before transport to the recycler: Carrying out sorting of the brominated fractions prior to sending the waste to the recycler would reduce or even eliminate the proportion of brominated plastics in the output fraction, making it more valuable, in addition to a corresponding reduction in transport costs and emissions.
- Management of the fine fraction [112]: Currently, the fine fraction below 10 mm usually ends up in landfill or incinerated. Therefore, reducing the number of shredding stages and choosing an appropriate shredding technology would reduce the amount of this fraction produced. In addition, pre-sorting of plastics and separation of the brominated fractions before transport would contribute to this reduction. In any case, effective sorting technologies exist in the 2-10 mm range (air table, wet shaker table, triboelectric sorting, magnetic and eddy current sorting, flotation and centrifugal sorting). Therefore, one possible way to improve the recyclability of these plastics would be through sourcing or finding recyclers with the appropriate technology.

5.4.2. Potential Pathways and main actors

Currently, the conventional WEEE plastic waste management system in Europe comprises, as shown in Figure 27. Current WEEE plastics management system. Own elaboration based on [75], the following stages:

Collection [119]**:**

The collection phase consists of a number of WEEE collection systems. This may include dedicated collection points at recycling centres, drop-off points at retail outlets or scheduled collection events.

In Europe, most collection schemes for household appliances have been set up in cooperation with municipal collection schemes for recyclables and household hazardous waste, in addition to some collection schemes operated by retailers. Some countries have prioritised collection through reuse centres, while others rely on scrap dealers as an important collection route.

Dismantling/Disassembly and sorting [71,119,120]**:**

After collection, WEEE undergoes disassembly and sorting processes, which separates the different types of equipment and materials of which WEEE is composed in order to facilitate the subsequent handling of plastics.

To this end, the different components and materials present in electronic equipment are identified and selected. During the disassembly of WEEE, techniques such as unscrewing, manual cutting and separation, cable disconnection, and component extraction are employed. These techniques allow for the safe and efficient separation of components and materials present in the equipment. Additionally, specialized machinery such as shredders or automated disassembly equipment may be used in certain cases to streamline the process.

Waste trading [75,119,121,122]**:**

It is during this stage that the purchase, sale and transfer of the plastic waste mixture generated in the previous phase takes place. Different actors such as recyclers, waste management companies, intermediaries and other participants in the waste management value chain can be involved during this stage.

The aim of this phase is to facilitate the recovery and recycling of these materials and to ensure that they are sent to appropriate recycling or recovery facilities in compliance with regulations. However, a very common practice as a consequence of a number of reasons, such as insufficient capacity to manage all the waste that is generated, leads to the export of waste to other countries that in many cases are not authorised or do not have the appropriate infrastructure, which can result in environmental and social problems.

Plastic sorting [75,116,119,122]**:**

In this phase, plastic waste electrical and electronic equipment (WEEE) undergoes a sorting process. This process involves separating the different types of plastics present in WEEE. Sorting can be carried out in a variety of ways, usually chosen according to the size and objectives of the facility. The main options available include manual sorting, by visual identification and separation of plastics, and automated techniques such as density separation or magnetic separation.

Plastic treatment and Recycling / Energy recovery [75,116,120,122]**:**

Once segregated, the plastics undergo treatment to prepare them for recycling or energy recovery. This usually involves shredding the plastics into smaller pieces to facilitate further processing, as well as washing to remove contaminants and impurities, followed by drying and granulation to produce uniform plastic flakes or granules.

After this pre-treatment, the plastics are sent to specialised recycling facilities to undergo various techniques, such as melting, extrusion or moulding, to transform them into new plastic products or raw materials for manufacturing. The recycling process may involve mixing the WEEE plastics with virgin plastics to meet specific quality and performance requirements.

There are multiple treatments, the choice of which depends on several factors such as the quality and composition of the WEEE plastics, the availability of treatment technologies, regulatory requirements, and environmental considerations. In any case, mechanical recycling is the most used treatment for WEEE plastics. In this process, plastics undergo shredding, washing, drying and granulation to obtain recycled plastic granules.

In cases where plastics from WEEE cannot be recycled, they are often subjected to energy recovery methods by thermal treatment/pyrolysis or to landfill disposal.

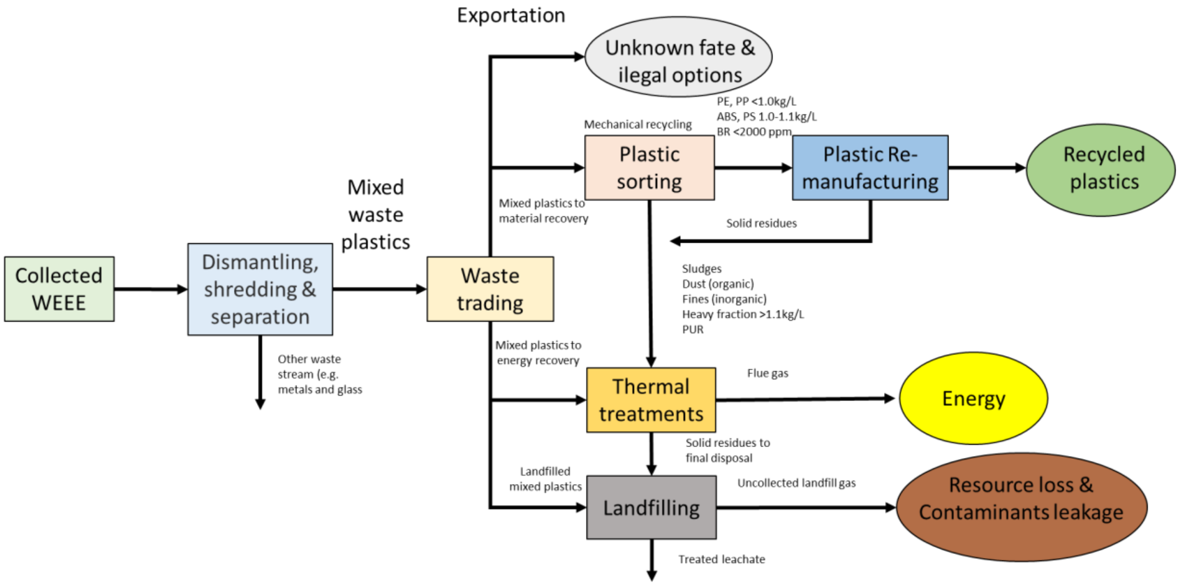


Figure 27. Current WEEE plastics management system. Own elaboration based on [75]

The WEEE plastics management system is based on the collaboration and fulfilment of the responsibilities of several key stakeholders who play a crucial role in ensuring the efficient handling and sustainable management of these plastic waste streams. These stakeholders encompass actors from different sectors, each with their own responsibilities, perspectives and contributions. These actors collectively address the challenges and opportunities of the transition to a more circular economy for WEEE plastics.

The most important actors in this system are grouped into 5 types, according to the phase for which they are responsible. The composition of these groups is shown in the following diagram:

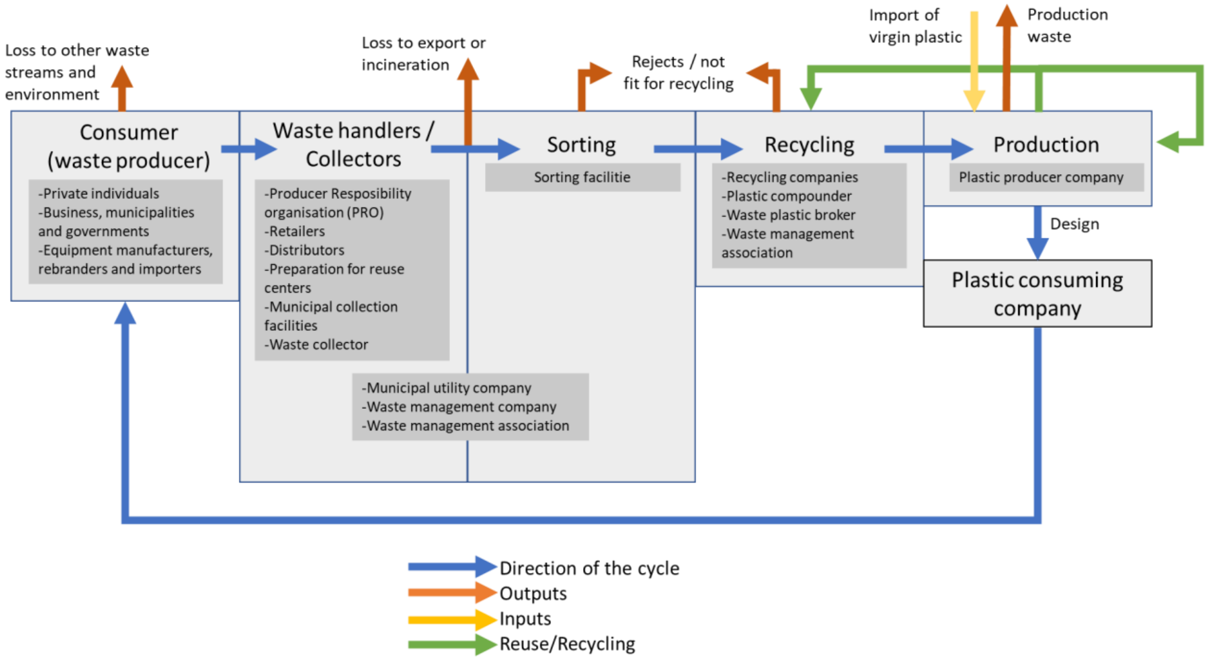


Figure 28. Main actors groups along the WEEE plastics management stream Own elaboration based on [123,124]

In turn, these actors have, as reflected in Table 11, a series of responsibilities, barriers and opportunities that are highly related to the improvement of the system.

Table 11. Roles/responsibilities of the main stakeholder groups in the management of plastics from WEEE, as well as aspects relevant to its quality.

Actor	Roles and Responsibilities [123,125]	Barriers [124,126–129]	Opportunities[124–127]
Consumer (waste producer)	Ensure proper disposal of WEEE by either delivering it to designated collection points or selling it to a licensed commercial collector or recycler.	-Lack of awareness and trust -Inconvenient or impractical collection sites -Data security concerns	-Education and awareness-raising -Participation in recycling programmes -Promoting sustainable products through their purchasing choices -Reduce hoarding -Economic incentives
Waste handling / Collectors / PROs / Retailers	Proper collection and transportation of the WEEE to which they have access.	-Limited infrastructure and logistics -Lack of capacity -The need for adequate training in safe management -Mixing with other types of waste -No declarations as WEEE -Illegal exports	-Design customized collection solutions. -Contribute to incentives aimed at improving the quality of collection. -Strengthen the connection between the consumer and the sorting plant. -Foster technology development.
Sorting facility	Receiving the collected WEEE and sorting them into different material streams, including plastics	-Mixing with other types of waste -Limitations in terms of technology and processing capacity -Difficult classification of WEEE plastic waste due to the presence of different additives and types of plastics with different characteristics and properties.	-Collaboration with other actors -Incentives for establishing sufficient capacity -Technology development -Report any WEEE received and its fate
Recycler / Compounder	Receiving the sorted plastics from WEEE and processing them for recycling.	-Insufficient industrial waste availability for cleaner and more homogeneous plastic. -Security of supply – irregular supply in quality and quantity -The management of WEEE plastics can involve significant costs. -Diversity of materials and technologies -The presence of unwanted substances can affect the quality of waste.	-Technology development -Incentives for establishing sufficient capacity -Collaboration with other actors -Obtaining certifications and complying with standards -Report any WEEE received and its fate

Producer	Production of the EEE by considering durability, repairability, and the use of recyclable materials in their products.	-Security of supply in quality and quantity -Development cost for integrating use of recycled plastics in production -Logistical and financial challenges	-Designing products that are easier to recycle and dismantle -Implementation of business models based on the reuse, recycling and remanufacturing of products -Development of new technologies and materials to facilitate the management and recycling of WEEE plastics. -Collaboration with other actors

As presented above, there is a whole regulatory framework aimed at ensuring the proper and sustainable disposal of this waste, promoting the recovery and recycling of these plastic materials. From a legal point of view, the most important are the criteria for the separation and sorting of plastics from WEEE in the Waste Electrical and Electronic Equipment (WEEE) Directive, the limitation of hazardous substances in the RoHS Directive and in the REACH regulation.

However, it is considered by many actors in the system that this framework is not comprehensive enough to be able to guarantee the quality in the management of WEEE plastic waste. Consequently, and as can be seen from the results obtained in the surveys carried out in the European Commission's Study on Quality Standards for the Treatment of Waste Electrical and Electronic Equipment (WEEE), according to which of the 2860 WEEE treatment facilities operating during 2019 and 2020, companies, facilities or countries have resorted to other standards in order to achieve the quality levels they are looking for [130]:

- 634 of these WEEE treatment facilities work in compliance with the requirements of the CENELEC/WEEELABEX standards, 179 facilities hold a valid certificate of compliance issued by the WEEELABEX organisation and the remaining facilities are considered working in compliance with the CENELEC/WEEELABEX standards,
- Nine Member States were identified as having adopted national minimum treatment requirements going beyond those of the WEEE Directive (Austria, Belgium, Germany, France, Ireland, Luxembourg, Portugal, Slovakia and Spain).
- Five Member States, namely Ireland, France, the Netherlands, Slovenia and most recently Lithuania made compliance with the EN 50625 series or the previous WEEELABEX standards obligatory by law.

Furthermore, the latter standard, EN 50625, which deals with the management of waste electrical and electronic equipment in general, together with EN 50614, which focuses on the reuse of waste electrical and electronic equipment, and the CENELEC set of standards covering the collection, transport, preparation for reuse and treatment of WEEE, are considered by the WEEE forum to be of vital importance and should be legally required to be complied with by facilities collecting, handling and treating WEEE [131].

From the information gathered so far, it is clear that there are many possibilities to improve the current management system, as reflected in section 4.4.1 and Table 11.

Based on the diagram of the current situation of the system shown in Figure 27, and incorporating some of the more developed technological opportunities, Figure 29 shows a future scenario that, together with the corresponding increases in capacity, would improve the separation of the plastic mixture, the quantity of plastic that is finally recycled and the quality of the plastic, all of this accompanied by a smaller quantity of plastics being exported.

In this scenario, the process would start, as it does today, with the collection of WEEE, only with a larger quantity of WEEE thanks to more aware producers and more efficient collection systems.

WEEE would follow the usual dismantling process, except that in the case of dealing with specific end-of-life products, there is the possibility to apply a sorting of plastic components to be extracted prior to the common shredding of the waste. This selected plastic fraction would follow its own pathway, during which it would undergo a process of sorting, shredding, potentially accompanied by a purification process. In this way, it would be possible to obtain different types of granules of high quality and/or with certain properties of interest [58,71].

Either the remaining fraction from the dismantling or the total collected WEEE in the case of not applying the previous strategy, would undergo a separation process, probably involving shredding, which would separate the plastic fraction from the rest of the materials (e.g., metals and glass).

At this point, waste trading would take place, during which efforts would be made to avoid as much waste being exported abroad as possible, given the impacts this can have.

The mixture of plastics for recovery would be sorted according to their density differences. The light fraction would be remanufactured into recycled plastics. Only Polyurethane (PUR), which due to certain characteristics and properties makes it more challenging to remanufacture compared to other plastics in the light fraction, together with the solid residues from remanufacturing would be thermally treated for energy recovery.

Regarding the heavy fraction, it undergoes a second phase of density separation and optical detection, resulting in the following fractions [122]:

- ABS, Polystyrene (PS), PC/ABS, with density between 1,1kg/L and 1,25kg/L which are sent to the CreaSolv® process. Process that consists of dissolving plastics, allowing the individual recovery of the components and after a process of "purification or upgrading", their reuse in the manufacture of new products.
- Soft Polyvinyl chloride (PVC) and Polymethyl methacrylate (PMMA), with density between 1.1 kg/L and 1.25 kg/L, together with PVC with density > 1.25 kg/L and other plastics, which with the undissolved material coming from the CreaSolv® process are sent to Modix extrusion pre-treatment before pyrolysis. The remaining residues from the waste plastics sorting process, such as sludge, dusts and fines, are also sent to pyrolysis process, after a preliminary drying.

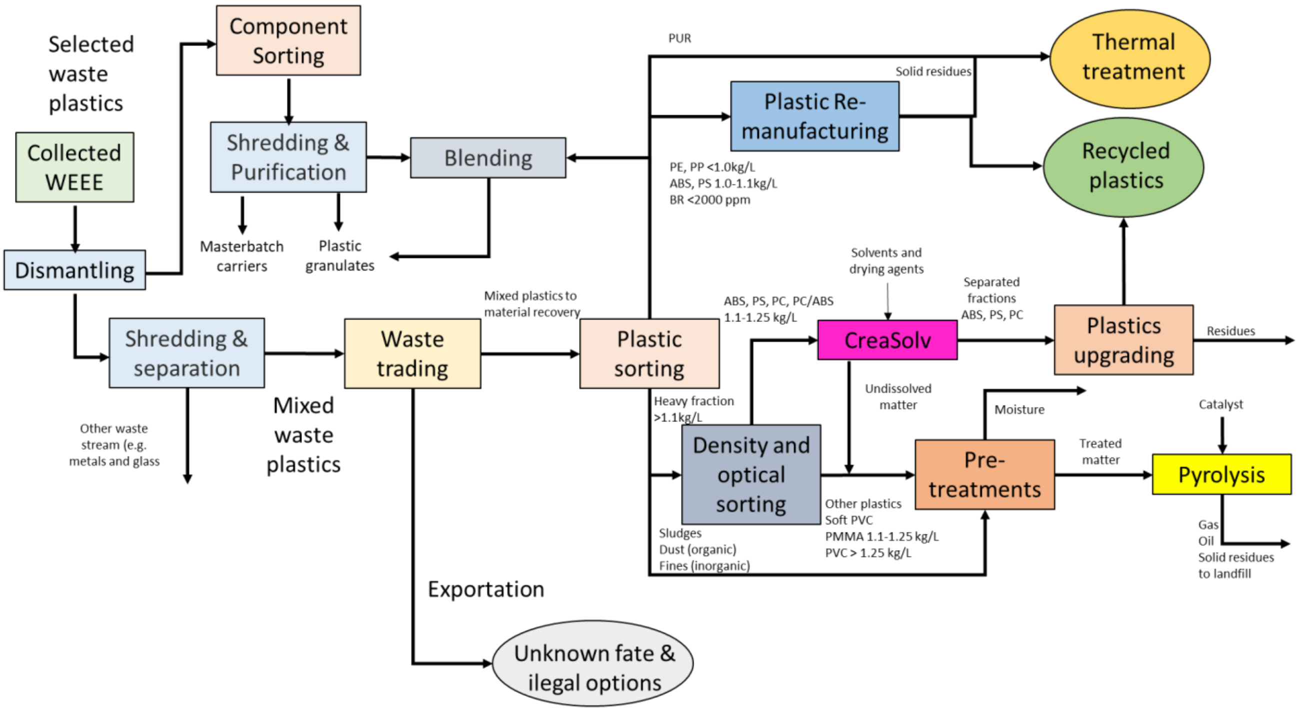


Figure 29. Potential pathways of the WEEE plastics management system. Own elaboration based on [58,122]

6. Discussion

Considering the limitations of information encountered during the development of this deliverable, the current regulatory framework status for each sector is presented below, following the methodology described in section 2. An explanatory table with the criteria and grading system proposed by the EEA is in the Annex section. Higher grading (3) means a better regulatory scenario in the respective criterion. As stated above and illustrated in the graph below, the regulatory framework for these secondary materials demonstrates a low to medium level of effectiveness, as it does not reach the classification of "well-functioning."

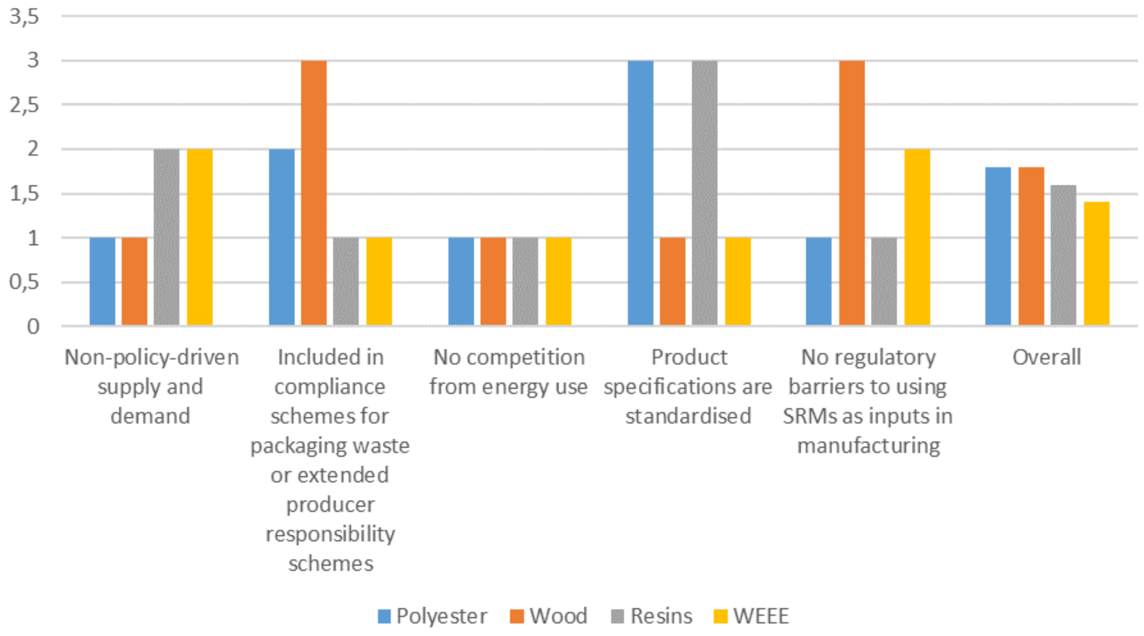


Figure 30. Sectoral results of the regulatory framework analysis

Furthermore, it is noteworthy that energy recovery competes vigorously with all sectors of the studied secondary materials, as all sectors were market with the lowest grade “1” (see Annex for the detailed explanation of the grading system and criterion).

Regarding the rest of the criteria, it can be observed that among these markets, the most dependent on policies that exogenously drive demand and/or supply or modify prices would be polyester and wood. In contrast, the materials in these two sectors would, unlike the other two, be subject to EPR schemes or be involved in closed-loop circular schemes. However, of these two, only polyester, as well as resins, have standardised product specifications, as these are highly industrialized and well-established value chains. Finally, it should be noted that despite having these specifications, polyesters and resins are the secondary materials with the greatest regulatory barriers or difficulties to be reintroduced into manufacturing, followed by plastics from WEEE.

These results are in agreement with the analysis conducted by the EEA [27], where several key challenges were identified in the markets for secondary materials. These challenges primarily stem from their relatively small size and decentralized character compared to primary materials, resulting in weak demand and an overall lack of standardized specifications for the waste streams, as well as underdeveloped and often volatile supply chain network (collection, separation, sorting steps) and the lack of harmonized certification schemes. Consequently, the quality of materials available for industrial use is adversely affected. Furthermore, specific materials encounter unique difficulties, such as competing demand for energy usage.

Additionally, the potential uses and markets where these materials can or will be applied are outlined based on the information received from the demos (section 3) and the data collected on recycling/reuse and upcycling opportunities (section 5):

Polyesters

Polyester is one of the most commonly used plastics in the world, with applications in products such as bottles, carpets, and clothing. However, currently, 91% of all polyester products are not recycled because they are colored, contaminated or contain additives [80]. This results in a large amount of waste every year. In Europe, about one third of textile waste is collected separately, and a large part is exported for reuse or recycling abroad [132]. While percentages vary between countries, about 60-70 % of all collected textiles are reused (locally or abroad), 10-30 % are recycled and 10-20 % are incinerated for energy recovery or landfilled.

To address this issue, there are several initiatives and companies working on developing new methods for recycling, reusing and upcycling polyester. One example is CuRe Technology, a company based in the Netherlands that is working on developing a fully circular polyester chain, with a range of methods for recycling the basic material depending on its precise specifications. The company has its own core technology but also allows for modular add-on to other technologies, giving the flexibility to choose the best route depending on the type of polyester waste [133].

Another example is ReHubs, an initiative by EURATEX that plans to pursue fiber-to-fiber recycling for 2.5 million tons of textile waste by 2030. The textile recycling industry could generate around 15,000 direct new jobs by 2030 in Europe and increase the need for nearshoring and reshoring of textile manufacturing. The textile recycling industry in Europe could reach economic, social and environmental benefits for €3.5 billion to €4.5 billion by 2030 [134].

Upcycling routes for polyester are also being explored. For example, a Northwestern University-led team has provided the basis for a technique to enhance the effects of an enzyme that breaks down polyester into its fundamental parts [135].

The European Union has implemented several measures to promote the reuse, recycling, and upcycling of polyesters. One of the main building blocks of the European Green Deal is the new circular economy action plan (CEAP), which was adopted by the European Commission in March 2020. The CEAP aims to reduce pressure on natural resources and create sustainable growth and jobs, while also achieving the EU’s 2050 climate neutrality target and halting biodiversity loss. The action plan introduces legislative and non-legislative measures targeting areas where action at the EU level brings real added value [136].

The EU’s rules on packaging and packaging waste cover both packaging design and packaging waste management, with the aim of dealing with the increasing quantities of packaging waste, which cause environmental problems [137]. The rules regulate what kind of packaging can be placed on the EU market, as well as packaging waste management and packaging waste prevention measures. The Packaging Directive sets specific targets for recycling, including a target of 50% for plastic by 2025 and 55% by 2030.

In addition to these measures, the EU has also implemented other initiatives to promote the circular economy, such as the Waste Framework Directive, which introduces an order of preference for waste management called the “waste hierarchy”. These initiatives aim to create a more sustainable future for materials such as polyester by promoting their reuse, recycling, and upcycling [138].

In conclusion, there are several challenges and opportunities that citizens, companies and policymakers will have to face in the coming years regarding the reuse, recycling and upcycling of polyesters in the European Union. However, there are already several initiatives and companies working on developing new methods to address these challenges and create a more sustainable future for polyester. Upcycling routes for polyester might produce other value-added goods for the market.

Wood

The lowest values in the market assessment have been obtained in non-policy driven supply and demand, No competition of energy use and Standardised product specifications, resulting in an overall score of "Average status".

However, wood waste is one of the most valuable wastes in two important aspects: on the one hand, wood materials are included in compliance systems for packaging waste, as it is one of the most important packaging materials to achieve a real circular economy in many value chains [139,140]; on the other hand, there are no regulatory barriers to use wood SRMs, as it is a material with a large number of different uses, such as the wood industry, biomass fuels for industry and households, paper and board industry, etc.

Nevertheless, there are many efforts to be addressed, especially to regulate the use of this wood, prioritising the waste hierarchy from EU regulation, and leaving energy uses only for non-recoverable materials.

Resins

The high variability of resins types and applications in the market, as well as the fact that they are mostly part of multimaterial pieces that range from wood panels to technical composites and that resins act as “glue” by hardening into a thermoset (that cannot be re-melted such as thermoplastic materials, e.g. PE, PET, etc) complicates the development of secondary markets using said materials. Nonetheless, given their importance in our society and the undeniable fact that millions of tons of resins and composites are being currently incinerated or landfilled, both regulations and technological solutions are moving towards the development of more sustainable, circular value chains within the sector.

There is currently no specific EU regulation addressing resins. Nonetheless, various regulatory frameworks can be applied to resin-containing materials, such as the waste framework, landfill framework, construction products framework, eco-design directive, EU green deal / sustainable chemistry strategies etc. In this context, there is a clear incentive and urgency to find solutions for materials that cannot be landfilled from 2025 onwards, both by maximizing the reuse and low-energy recycling possibilities as well as by developing new efficient recycling technologies to obtain high value products from resin wastes. Furthermore, tight REACH regulations and further envisioned restrictions in chemical building blocks widely used in resin formulations, e.g., formaldehyde, BPA and other phenols, melamine, etc., also incentivize the development of more sustainable and safer resins from biobased molecules and polymers (e.g., lignin, proteins, tannin, furans). Finally, advanced solutions tackle the development of reprocessable thermosets by the addition of dynamic covalent bonds. While not envisioned commercially in the near future, these developments show the engagement of both scientific community and industries on novel value chains. Parallel to advances in the manufacturing of resins, establishing new supply chains where secondary raw materials are readily available and have standard properties is a current challenge that needs major efforts in terms of new harmonized standards, certification schemes, and the efficient collection, separation and sorting of waste streams.

Overall, it is of paramount importance that said innovations and supply chains are backed up by a strong regulatory framework and support from society, policymakers and governmental stakeholders in order to deploy new technologies in a reasonable timeframe and with the needed viability, scalability and replicability.

WEEE Plastics

Faced with these state and other shortcomings outside the regulatory framework, the sector has demonstrated, as shown above, its interest in resorting to standards that go further than what the current directives can achieve in their current state.

On this basis, together with the identification and application of different opportunities to combat the barriers experienced by the different main actors that make up the management system, as well as the development of technologies, the aim is to increase the capacity that the sector is capable of assimilating, while at the same time improving the recycling and recycling rates.

Taking all this into account, together with the data provided by the demo and the dependence on their quality and specific characteristics, it is considered that from the multiple final forms (e.g., New injection moulded plastic components, pure polymers obtained through the recycling process, Masterwatch carriers, Plastic granulates, …) they can take , the following end uses and markets are those where secondary plastics from WEEE will have the greatest potential for acceptance and demand:

- Small and large domestic appliance equipment
- Transportation (automotive passengers transportation, light and heavy commercial vehicles, agriculture and construction tractors)
- Building materials
- Packaging
- Furniture
- Toys and sporting goods
- General purposes

7. Conclusions

The objective of this report was to analyze four different sectors (polyester, wood, resins and WEEE) among EU regulations to check whether secondary markets are suitable, and to provide potential pathways and main actors based on recycling/reuse and upcycling opportunities. In the context of the EU-funded DigInTrace project (grant No 101091801), new circular value chains are proposed to increase the sustainability of said sectors and enable products' traceability along the full value chain.

The waste streams of interest in each sector were introduced and a thorough evaluation of the EU regulatory framework per sector was done, having as base a methodology from the European Environmental Agency (EEA) for the quantitative assessment of secondary raw material markets. Results show that the regulatory frameworks for the targeted secondary raw materials have a current low to medium level of effectiveness. Accordingly, the main aspects hindering a well-functioning scenario are the strong competition with energy (waste incineration), the lack of standards and stricter EPR in some sectors, and the regulatory barriers for re-introducing secondary raw materials in value chains. Furthermore, reuse, recycling and upcycling opportunities were explored for each waste stream. Finally, based on the regulatory landscape and technological maturity, possible pathways and main actors were defined for each of the sectors.

While there is a clear movement towards the transition to novel circular value chains, major efforts are still needed to realize resilient and stable supply chain networks for secondary raw materials, as well as achieve efficient levels of separation, sorting and recycling to yield high value products from waste streams. Outside the regulatory space, there are clear technical challenges that need to be tackled so that materials' loops are closed efficiently and feasibly. The DigInTrace project aims at bridging the current gaps by addressing the upcycling of polyester into high tenacity fibers, developing new products by valorizing wood-byproducts, developing new resins of higher biobased content using agricultural byproducts, and recycling valuable thermoplastics from WEEE waste streams. The strong focus on sorting steps and the development of digital frameworks, digital product passports and smart tags aim the development of processes that are not only circular but also transparent, where traceability is a core concept embedded in the products.

It should be noted that the potential markets for SRM in the studied waste streams need to be reinforced by a common regulation that allows actors to use these materials without significant barriers in their daily production processes, also in a transboundary scope. To this end, it is also important to highlight that EU regulations should be clear and establish an easy context to all members, in order to exchange the SRM between the actors involved in the different value chains. This is important for local and regional value chains, where the interaction between actors should be fluid to facilitate the use of this type of products.

Furthermore, it is essential to develop new forms of communication between actors with different tools, such as digital product passports to share information on available SMRs in local and regional contexts. In this sense, local public administrations must work on promoting opportunities and disseminating them among the community.

8. References

1. Palacios-Mateo, C.; van der Meer, Y.; Seide, G. Analysis of the Polyester Clothing Value Chain to Identify Key Intervention Points for Sustainability. *Environmental Sciences Europe 2021 33:1* **2021**, *33*, 1–25, doi:10.1186/S12302-020-00447-X.

2. Sadasivuni, K.K.; Hegazy, S.M.; Abdullah Aly, Aa.A.M.; Waseem, S.; Karthik, K. Polymers in Electronics. *Polymer Science and Innovative Applications: Materials, Techniques, and Future Developments* **2020**, 365–392, doi:10.1016/B978-0-12-816808-0.00011-1.

3. Kulkarni, G.S. Introduction to Polymer and Their Recycling Techniques. *Recycling of Polyurethane Foams* **2018**, 1–16, doi:10.1016/B978-0-323-51133-9.00001-2.

4. 9 Uses of Polyester and Their Differences | Xometry Available online: https://www.xometry.com/resources/materials/uses-of-polyester/ (accessed on 9 May 2023).

5. What Is Polyester Fabric: Properties, How Its Made and Where | Sewport Available online: https://sewport.com/fabrics-directory/polyester-fabric (accessed on 9 May 2023).

6. Nisticò, R. Polyethylene Terephthalate (PET) in the Packaging Industry. *Polym Test* **2020**, *90*, 106707, doi:10.1016/J.POLYMERTESTING.2020.106707.

7. PET Production Capacity Worldwide 2024 | Statista Available online: https://www.statista.com/statistics/242764/global-polyethylene-terephthalate-production-capacity/ (accessed on 9 May 2023).

8. Recycled Polyester Yarn: RPET Yarn - Textile Details Available online: https://textiledetails.com/recycled-polyester-yarn-rpet-yarn/ (accessed on 9 May 2023).

9. About Us • Plastics Europe Available online: https://plasticseurope.org/about-us/ (accessed on 9 May 2023).

10. Global-Plastic-Packaging-Market | Plastics News Available online: https://www.plasticsnews.com/article/20190128/FYI/190129903/global-plastic-packaging-market (accessed on 18 July 2023).

11. Plastics and Packaging Laws in the European Union | CMS Expert Guide Available online: https://cms.law/en/int/expert-guides/plastics-and-packaging-laws/european-union (accessed on 9 May 2023).

12. Mapping of Global Plastics Value Chain and Plastics Losses to the Environment: With a Particular Focus on Marine Environment | UNEP - UN Environment Programme Available online: https://www.unep.org/resources/report/mapping-global-plastics-value-chain-and-plastics-losses-environment-particular (accessed on 11 May 2023).

13. Man-Made Fibers Continue to Grow | Textile World Available online: https://www.textileworld.com/textile-world/fiber-world/2015/02/man-made-fibers-continue-to-grow/ (accessed on 18 July 2023).

14. European Environment Agency. Plastic in Textiles : Towards a Circular Economy for Synthetic Textiles in Europe.

15. Advanced Recycling: Opportunities for Growth | McKinsey Available online: https://www.mckinsey.com/industries/chemicals/our-insights/advanced-recycling-opportunities-for-growth (accessed on 18 July 2023).

16. Plastics Strategy Available online: https://environment.ec.europa.eu/strategy/plastics-strategy_en (accessed on 18 July 2023).

17. Packaging Waste Available online: https://environment.ec.europa.eu/topics/waste-and-recycling/packaging-waste_en (accessed on 18 July 2023).

18. Parliamentary Question | Final Guidelines for Directive (EU) 2019/904 on Single-Use Plastics: Checks on the Ex-Ante Analysis of Its Environmental Impact, Particularly on the Aquatic Environment | E-003099/2021 | European Parliament Available online: https://www.europarl.europa.eu/doceo/document/E-9-2021-003099_EN.html (accessed on 18 July 2023).

19. François Nègre *LA POLÍTICA AGRÍCOLA COMÚN EN CIFRAS*; 2023;

20. Zbieć, M.; Franc-Dąbrowska, J.; Drejerska, N. Wood Waste Management in Europe through the Lens of the Circular Bioeconomy. *Energies (Basel)* **2022**, *15*, doi:10.3390/en15124352.

21. FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS *Forest Products*; 2022;

22. European Commission *COMMISSION DECISION - of 18 December 2014 - Amending Decision 2000/ 532/ EC on the List of Waste Pursuant to Directive 2008/ 98/ EC of the European Parliament and of the Council*; 2014;

23. Interreg Europe Collection and Recycling of Construction and Demolition Waste: Key Learnings Available online: https://www.interregeurope.eu/find-policy-solutions/webinar/collection-and-recycling-of-construction-and-demolition-waste-key-learnings#:~:text=Construction%20and%20demolition%20waste%20(CDW,including%20hazardous%20materials%20like%20asbestos (accessed on 18 July 2023).

24. Dominique Boulday *D1.1 EUROPEAN WOOD WASTE STATISTICS REPORT FOR RECIPIENT AND MODEL REGIONS*;

25. Jain, A.; Sarsaiya, S.; Kumar Awasthi, M.; Singh, R.; Rajput, R.; Mishra, U.C.; Chen, J.; Shi, J. Bioenergy and Bio-Products from Bio-Waste and Its Associated Modern Circular Economy: Current Research Trends, Challenges, and Future Outlooks. *Fuel* **2022**, *307*, 121859, doi:10.1016/J.FUEL.2021.121859.

26. European Commission Packaging Waste Available online: https://environment.ec.europa.eu/topics/waste-and-recycling/packaging-waste_en (accessed on 18 July 2023).

27. EEA Investigating Europe′s Secondary Raw Material Markets.; 2022.

28. Sandberg, D. Additives in Wood Products—Today and Future Development. In *Environmental Footprints and Eco-Design of Products and Processes*; Springer, 2016; pp. 105–172.

29. formacare Factsheets on Formaldehyde Available online: https://www.formacare.eu/about-formaldehyde/factsheets/ (accessed on 6 June 2023).

30. European Chemicals Agency *ANNEX XV RESTRICTION REPORT-Formaldehyde and Formaldehyde Releasers*; 2019;

31. Grand view research *Formaldehyde Market Size, Share & Trends Analysis Report by Derivatives (Urea Formaldehyde, Melamine Formaldehyde), By End-Use (Building & Construction, Furniture, Automotive), By Region, And Segment Forecasts, 2021 - 2028*;

32. Eurostat PRODCOM - STATISTICS BY PRODUCT Available online: https://ec.europa.eu/eurostat/web/prodcom/database (accessed on 6 June 2023).

33. Lammens, Tijs.; Parisi, Claudia.; Ronzon, T.; Spekreijse, Jurjen.; Vis, Martijn.; European Commission. Joint Research Centre. *Insights into the European Market for Bio-Based Chemicals : Analysis Based on 10 Key Product Categories.*; ISBN 9789279984198.

34. EUR-Lex EU Waste Management Law Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=LEGISSUM:ev0010 (accessed on 6 June 2023).

35. *DIRECTIVE (EU) 2018/851 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 May 2018 Amending Directive 2008/98/EC on Waste (Text with EEA Relevance)*.

36. European Commission EU Construction and Demolition Waste Protocol and Guidelines Available online: https://single-market-economy.ec.europa.eu/news/eu-construction-and-demolition-waste-protocol-2018-09-18_en (accessed on 6 June 2023).

37. Official Journal of the European Union Separate Collection of Household Hazardous Waste Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52020XC1106(01) (accessed on 6 June 2023).

38. Official Journal of the European Communities *Council DIRECTIVE 1999/31/EC of 26 April 1999 on the Landfill of Waste*;

39. Official Journal of the European Union DIRECTIVE 2010/75/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 24 November 2010 on Industrial Emissions (Integrated Pollution Prevention and Control) Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32010L0075 (accessed on 6 June 2023).

40. Raunkjaer Stubdrup, K.; Karlis, P.; Roudier, S.; Delgado Sancho, L. Best Available Techniques (BAT) Reference Document for the Production of Wood-Based Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control). **2010**, doi:10.2791/21807.

41. European Commission *Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL Establishing a Framework for Setting Ecodesign Requirements for Sustainable Products and Repealing Directive 2009/125/EC*; 2022;

42. European Commission *Proposal for a Regulation Laying down Harmonised Conditions for the Marketing of Construction Products, Amending Regulation (EU) 2019/1020 and Repealing Regulation (EU) 305/2011*; 2022;

43. ECHA Registry of Restriction Intentions until Outcome Available online: https://echa.europa.eu/registry-of-restriction-intentions/-/dislist/details/0b0236e182439477 (accessed on 20 July 2023).

44. THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION Regulation_66_2010_25_11_2009_on the EU Ecolabel. *Official Journal of the European Union* **2010**.

45. CIRCABC *Criteria for Furniture*; 2023;

46. European Commission The European Green Deal. **2019**.

47. European Commission *A New Circular Economy Action Plan*; 2020;

48. European Commission Sustainable Carbon Cycles - Overview.

49. UN environment programme The Life Cycle Initiative Available online: https://www.unep.org/explore-topics/resource-efficiency/what-we-do/life-cycle-initiative (accessed on 20 July 2023).

50. European Commission *Chemicals Strategy for Sustainability Towards a Toxic-Free Environment*; 2020;

51. eurostat Waste Statistics - Electrical and Electronic Equipment Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics_-_electrical_and_electronic_equipment#Electrical_and_electronic_equipment_.28EEE.29_put_on_the_market_and_WEEE_processed_in_the_EU (accessed on 3 May 2023).

52. Ahirwar, R.; Tripathi, A.K. E-Waste Management: A Review of Recycling Process, Environmental and Occupational Health Hazards, and Potential Solutions. *Environ Nanotechnol Monit Manag* **2021**, *15*, 100409, doi:10.1016/J.ENMM.2020.100409.

53. Chaine, C.; Hursthouse, A.S.; McLean, B.; McLellan, I.; McMahon, B.; McNulty, J.; Miller, J.; Viza, E. Recycling Plastics from WEEE: A Review of the Environmental and Human Health Challenges Associated with Brominated Flame Retardants. *Int J Environ Res Public Health* 2022, *19*.

54. Goosey, E.; Goosey, M. The Materials of Waste Electrical and Electronic Equipment. *Waste Electrical and Electronic Equipment (WEEE) Handbook* **2019**, 231–262, doi:10.1016/B978-0-08-102158-3.00008-2.

55. Haarman, A.; Magalini, F.; Courtois, J. *Study on the Impacts of Brominated Flame Retardants on the Recycling of WEEE Plastics in Europe*;

56. Andreas Bill, A.; Gasser, M.; Haarman, A.; Böni Empa, H. *Processing of WEEE Plastics A Practical Handbook Turning Waste into Resources for Development SRI Builds Capacity for Sustainable Recycling in Developing Countries*; 2019; ISBN 978-3-906177-22-9.

57. MGG Plastics from WEEE Available online: https://mgg-recycling.com/recycling-services/plastics-from-weee/ (accessed on 3 May 2023).

58. Wagner, F.; Peeters, J.R.; De Keyzer, J.; Janssens, K.; Duflou, J.R.; Dewulf, W. Towards a More Circular Economy for WEEE Plastics – Part A: Development of Innovative Recycling Strategies. *Waste Management* **2019**, *100*, 269–277, doi:10.1016/J.WASMAN.2019.09.026.

59. Alassali, A.; Picuno, C.; Samara, H.; Diedler, S.; Fiore, S.; Kuchta, K. Antimony Mining from PET Bottles and E-Waste Plastic Fractions. *Sustainability (Switzerland)* **2019**, *11*, doi:10.3390/su11154021.

60. Alassali, A.; Abis, M.; Fiore, S.; Kuchta, K. Classification of Plastic Waste Originated from Waste Electric and Electronic Equipment Based on the Concentration of Antimony. *J Hazard Mater* **2019**, *380*, 120874, doi:10.1016/J.JHAZMAT.2019.120874.

61. European Commission Waste from Electrical and Electronic Equipment (WEEE) Available online: https://environment.ec.europa.eu/topics/waste-and-recycling/waste-electrical-and-electronic-equipment-weee_en (accessed on 3 May 2023).

62. Barouta, D.; Alassali, A.; Picuno, C.; Bruno, M.; Syranidou, E.; Fiore, S.; Kuchta, K. E-Plastics in a Circular Economy: A Comprehensive Regulatory Review. *J Clean Prod* **2022**, *355*, 131711, doi:10.1016/J.JCLEPRO.2022.131711.

63. European Commission *DIRECTIVE 2012/19/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 4 July 2012 on Waste Electrical and Electronic Equipment (WEEE)*;

64. Freegard, K.; Huisman, J. *Develop a Process to Separate Brominated Flame Retardants from WEEE Polymers*; 2005;

65. European Commission Restriction of Hazardous Substances in Electrical and Electronic Equipment (RoHS) Available online: https://environment.ec.europa.eu/topics/waste-and-recycling/rohs-directive_en (accessed on 4 May 2023).

66. European Commission *DIRECTIVE 2011/65/EU of the European Parliament and of the Council of June 2011 on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment*; 2011;

67. European Commission REGULATION (EC) No 1907/2006 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 18 December 2006. **2006**.

68. European Commission REACH Regulation Available online: https://environment.ec.europa.eu/topics/chemicals/reach-regulation_en#objectives (accessed on 26 May 2023).

69. de Römph, T.; Van Calster, G. REACH in a Circular Economy: The Obstacles for Plastics Recyclers and Regulators. *Review of European* **2018**, *27*, 267–277.

70. Digital Europe *Best Practices in Recycled Plastics*; 2016;

71. Wagner, F.; Peeters, J.R.; De Keyzer, J.; Janssens, K.; Duflou, J.R.; Dewulf, W. Towards a More Circular Economy for WEEE Plastics – Part B: Assessment of the Technical Feasibility of Recycling Strategies. *Waste Management* **2019**, *96*, 206–214, doi:10.1016/J.WASMAN.2019.07.035.

72. WEEELABEX QUALITY STANDARDS FOR THE PROCESSING OF WEEE Available online: https://www.weeelabex.org/about-us/news-events/quality-standards-for-the-processing-of-weee/ (accessed on 17 July 2023).

73. *EU-WIDE UNIFORM CONDITIONS FOR THE PROPER QUALITY TREATMENT OF WEEE: A Call for Implementing Acts to Lay down Minimum Quality WEEE Treatment Standards in Strict Accordance with the European Standards*;

74. Baldé, C.P.; Iattoni, G.; Xu, C.; Yamamoto, T. *Update of WEEE Collection Rates, Targets, Flows, and Hoarding-2021*;

75. Cardamone, G.F.; Ardolino, F.; Arena, U. About the Environmental Sustainability of the European Management of WEEE Plastics. *Waste Management* **2021**, *126*, 119–132, doi:10.1016/J.WASMAN.2021.02.040.

76. Verschoor, J.-A.; Kusumawardhani, H.; Ram, A.F.J.; de Winde, J.H. Toward Microbial Recycling and Upcycling of Plastics: Prospects and Challenges. *Front Microbiol* **2022**, *13*.

77. Manavitehrani, I.; Fathi, A.; Badr, H.; Daly, S.; Shirazi, A.N.; Dehghani, F. Biomedical Applications of Biodegradable Polyesters. *Polymers (Basel)* 2016, *8*.

78. Schyns, Z.O.G.; Shaver, M.P. Mechanical Recycling of Packaging Plastics: A Review. *Macromol Rapid Commun* **2021**, *42*, 2000415, doi:https://doi.org/10.1002/marc.202000415.

79. Payne, J.; Jones, M.D. The Chemical Recycling of Polyesters for a Circular Plastics Economy: Challenges and Emerging Opportunities. *ChemSusChem* 2021, *14*, 4041–4070.

80. Dissanayake, D.G.K.; Weerasinghe, D.U. Fabric Waste Recycling: A Systematic Review of Methods, Applications, and Challenges. *Materials Circular Economy* **2021**.

81. Liu, F.; Gao, X.; Shi, R.; C. M. Tse, E.; Chen, Y. A General Electrochemical Strategy for Upcycling Polyester Plastics into Added-Value Chemicals by a CuCo2O4 Catalyst. *Green Chemistry* **2022**.

82. Hones, B.; Barbour, C.; Eike, R.J. *2020 Proceedings Virtual Conference Procedural Development for Chemical Separation of Cotton/Polyester Blends for Textile Recycling*; 2020;

83. Berk, Z. *Food Process Engineering and Technology*; Academic press, 2018; ISBN 0128120541.

84. Payne, J.; Jones, M.D. The Chemical Recycling of Polyesters for a Circular Plastics Economy: Challenges and Emerging Opportunities. *ChemSusChem* **2021**, *14*, 4041–4070, doi:https://doi.org/10.1002/cssc.202100400.

85. Verschoor, J.-A.; Kusumawardhani, H.; Ram, A.F.J.; de Winde, J.H. Toward Microbial Recycling and Upcycling of Plastics: Prospects and Challenges. *Front Microbiol* **2022**, *13*.

86. Plan, N.C.E.A. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions A New Circular Economy Action Plan For a Cleaner and More Competitive Europe. **2009**.

87. Elliott, T.; Gillie, H.; Thomson, A. Chapter 24 - European Union's Plastic Strategy and an Impact Assessment of the Proposed Directive on Tackling Single-Use Plastics Items. In *Plastic Waste and Recycling*; Letcher, T.M., Ed.; Academic Press, 2020; pp. 601–633 ISBN 978-0-12-817880-5.

88. Cocchi, M.; Vargas, M.; Tokacova, K. *Absorbing the Potential of Wood Waste in EU Regions and Industrial Bio-Based Ecosystems-BioReg*; 2019;

89. Wood Recyclers' Association WRA Grades of Waste Wood. **2023**.

90. European Commission Analysis of Certain Waste Streams and the Potential of Industrial Symbiosis to Promote Waste as a Resource for EU Industry. *Publications Office* **2015**, doi:10.2873/689189.

91. Berdnikova, P. V.; Zhizhina, E.G.; Pai, Z.P. Phenol-Formaldehyde Resins: Properties, Fields of Application, and Methods of Synthesis. *Catal Ind* **2021**, *13*, 119–124.

92. Bernardeau, F.; Perrin, D.; Caro-Bretelle, A.-S.; Benezet, J.-C.; Ienny, P. Development of a Recycling Solution for Waste Thermoset Material: Waste Source Study, Comminution Scheme and Filler Characterization. *Material Cycles and Waste Management* **2018**, *20*, 1320–1336.

93. Goldsberry, C. Yes! Thermoset Resins Can Be Recycled.

94. Yang, L.; Runt, J.; Kuo, M.; Huang, K.; Yeh, J. Regeneration and Utilization of Waste Phenolic Formaldehyde Resin: A Performance Investigation. *Applied polymer science* **2019**.

95. Mason, H. Recycling End-of-Life Composite Parts: New Methods, Markets.

96. Liu, M.; Wang, Y.; Wu, Y.; Wan, H. Hydrolysis and Recycling of Urea Formaldehyde Resin Residues. *J Hazard Mater* **2018**, *355*, 96–103, doi:10.1016/J.JHAZMAT.2018.05.019.

97. Wu, S.; Zhang, N.; Wang, C.; Hou, X.; Zhao, J.; Jia, S.; Zhao, J.; Cui, X.; Jin, H.; Deng, T. An Efficient and Mild Recycling of Waste Melamine Formaldehyde Foams by Alkaline Hydrolysis. *Green Energy & Environment* **2022**, doi:10.1016/J.GEE.2022.10.008.

98. Wu, S.; Zhang, N.; Jia, S.; Wang, C.; Wang, Y.; Qi, Y.; Wang, H.; Cui, X.; Hou, X.; Deng, T. Catalytic Degradation of Melamine–Formaldehyde Resins into Valuable Chemicals. *Green Chemistry* **2021**.

99. Cho, H.-K.; Sung Lim, J. Production and Characterization of Recycled Carbon from Phenol Resin Waste Using Supercritical Methanol. *Thermophysics* **2017**.

100. Post, W.; Susa, A.; Blaauw, R.; Molenveld, K.; Knoop, R.J.I. A Review on the Potential and Limitations of Recyclable Thermosets for Structural Applications. *Polymer Reviews* 2020, *60*, 359–388.

101. Gusse, A.C.; Miller, P.D.; Volk, T.J. White-Rot Fungi Demonstrate First Biodegradation of Phenolic Resin. *Environ. Sci. Technol.* **2006**, *40*, 4196–4199.

102. Helios Resins Bio-Based Resins on the Rise Available online: https://www.resinshelios.com/bio-based-resins-on-the-rise/ (accessed on 21 July 2023).

103. storaenso NeoLigno®: A Promising Bio-Based Alternative for Fossil-Based Binding Agents Available online: https://www.storaenso.com/en/newsroom/news/2023/6/neoligno-bio-based-alternative-for-fossil-based-binding-agents?utm_campaign=BM%2FNeoLigno&utm_content=251499828&utm_medium=social&utm_source=linkedin&hss_channel=lcp-34903065 (accessed on 21 July 2023).

104. Cardoso Borges, J.; Athanassiadou, E.; Tsiantzi, S. Bio-Based-Resins-for-Wood-Composites.

105. Solt, P.; Rößiger, B.; Konnerth, J.; van Herwijnen, H.W.G. Lignin Phenol Formaldehyde Resoles Using Base-Catalysed Depolymerized Kraft Lignin. *Polymers (Basel)* **2018**, *10*, doi:10.3390/polym10101162.

106. Li, C.; Zhang, J.; Yi, Z.; Yang, H.; Zhao, B.; Zhang, W.; Li, J. Preparation and Characterization of a Novel Environmentally Friendly Phenol–Formaldehyde Adhesive Modified with Tannin and Urea. *Int J Adhes Adhes* **2016**, *66*, 26–32, doi:10.1016/J.IJADHADH.2015.12.004.

107. Sarika, P.R.; Nancarrow, P.; Khansaheb, A.; Ibrahim, T. Bio-Based Alternatives to Phenol and Formaldehyde for the Production of Resins. *Polymers (Basel)* 2020, *12*, 1–24.

108. Reghunadhan Nair, C.P.; R. L.. Bindu; V. C., J. Cyanate Esters Based on Cardanol Modified-Phenol-Formaldehyde Resins: Syntheses and Thermal Characteristics. *Polym Chem* **1995**, *33*, 621–627.

109. Siahkamari, M.; Emmanuel, S.; Hodge, D.B.; Nejad, M. Lignin-Glyoxal: A Fully Biobased Formaldehyde-Free Wood Adhesive for Interior Engineered Wood Products. *ACS Sustain Chem Eng* **2022**, *10*, 3430–3441, doi:10.1021/acssuschemeng.1c06843.

110. Jiang, K.; Lei, Z.; Yi, M.; Lv, W.; Jing, M.; Feng, Q.; Tan, H.; Chen, Y.; Xiao, H. Improved Performance of Soy Protein Adhesive with Melamine-Urea-Formaldehyde Prepolymer. *RSC Adv* **2021**, *11*, 27126–27134, doi:10.1039/d1ra00850a.

111. Ghahri, S.; Hajihassani, R. Possibility of Replacing Urea Formaldehyde Resin by Soy Adhesive in Production of Plywood. *Wood and Forest Science Technology* **2021**, *28*, 111–129, doi:10.22069/JWFST.2021.19285.1933.

112. Maisel, F.; Chancerel, P.; Dimitrova, G.; Emmerich, J.; Nissen, N.F.; Schneider-Ramelow, M. Preparing WEEE Plastics for Recycling – How Optimal Particle Sizes in Pre-Processing Can Improve the Separation Efficiency of High Quality Plastics. *Resour Conserv Recycl* **2020**, *154*, doi:10.1016/j.resconrec.2019.104619.

113. Baxter, J.; Wahlstrom, M.; Castell Rüdenhausen, M. zu; Fråne, A. *WEEE Plastics Recycling*; 2015;

114. Truttmann, N.; Rechberger, H. Contribution to Resource Conservation by Reuse of Electrical and Electronic Household Appliances. *Resour Conserv Recycl* **2006**, *48*, 249–262, doi:10.1016/J.RESCONREC.2006.02.003.

115. Seyring, N.; Kling, M.; Weißenbacher, J.; Hestin, M.; Lecerf, L.; Magalini, F.; Sinha Khetriwal, D.; Kuehr, R. *Study on WEEE Recovery Targets, Preparation for Re-Use Targets and on the Method for Calculation of the Recovery Targets Final Report*;

116. Jia, C.; Das, P.; Kim, I.; Yoon, Y.J.; Tay, C.Y.; Lee, J.M. Applications, Treatments, and Reuse of Plastics from Electrical and Electronic Equipment. *Journal of Industrial and Engineering Chemistry* **2022**, *110*, 84–99, doi:10.1016/J.JIEC.2022.03.026.

117. Sahajwalla, V.; Gaikwad, V. The Present and Future of E-Waste Plastics Recycling. *Curr Opin Green Sustain Chem* **2018**, *13*, 102–107, doi:10.1016/J.COGSC.2018.06.006.

118. Hennebert, P.; Filella, M. WEEE Plastic Sorting for Bromine Essential to Enforce EU Regulation. *Waste Management* **2018**, *71*, 390–399, doi:10.1016/J.WASMAN.2017.09.031.

119. Salhofer, S.; Steuer, B.; Ramusch, R.; Beigl, P. WEEE Management in Europe and China – A Comparison. *Waste Management* **2016**, *57*, 27–35, doi:10.1016/J.WASMAN.2015.11.014.

120. Cui, J.; Forssberg, E. Mechanical Recycling of Waste Electric and Electronic Equipment: A Review. *J Hazard Mater* **2003**, *99*, 243–263, doi:10.1016/S0304-3894(03)00061-X.

121. Pan, X.; Wong, C.W.Y.; Li, C. Circular Economy Practices in the Waste Electrical and Electronic Equipment (WEEE) Industry: A Systematic Review and Future Research Agendas. *J Clean Prod* **2022**, *365*, 132671, doi:10.1016/J.JCLEPRO.2022.132671.

122. Ardolino, F.; Cardamone, G.F.; Arena, U. How to Enhance the Environmental Sustainability of WEEE Plastics Management: An LCA Study. *Waste Management* **2021**, *135*, 347–359, doi:10.1016/J.WASMAN.2021.09.021.

123. *D2.2 Analysis of the WEEE Value Chain Duration: 30 Months Identifier: D2.2 Report Summarising the Results of the Analysis of Electronics Value Chain Title: Analysis of the WEEE Value Chain*; 2016;

124. Milios, L.; Holm Christensen, L.; McKinnon, D.; Christensen, C.; Rasch, M.K.; Hallstrøm Eriksen, M. Plastic Recycling in the Nordics: A Value Chain Market Analysis. *Waste Management* **2018**, *76*, 180–189, doi:10.1016/J.WASMAN.2018.03.034.

125. WEEE-Forum *An Enhanced Definition of EPR and the Role of All Actors*; 2020;

126. Parajuly, K.; Kuehr, R.; Awasthi, A.K.; Fitzpatrick, C.; Lepawsky, J.; Smith, E.; Widmer, R.; Zeng, X. *Future E-Waste Scenarios*; ISBN 9789280891065.

127. Ghisellini, P.; Quinto, I.; Passaro, R.; Ulgiati, S. Circular Economy Management of Waste Electrical and Electronic Equipment (WEEE) in Italian Urban Systems: Comparison and Perspectives. *Sustainability* **2023**, *15*, 9054, doi:10.3390/su15119054.

128. Baldé, C.P.; Wagner, M.; Iattoni, G.; Kuehr, R. *In-Depth Review of the WEEE Collection Rates and Targets*;

129. CPA *STATE-OF-PLAY ON COLLECTED AND SORTED PLASTIC WASTE*;

130. European Commission STUDY ON QUALITY STANDARDS FOR THE TREATMENT OF WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT (WEEE)., doi:10.2779/69374.

131. WEEE-Forum WEEE Forum Position Letter to EC.

132. Nikolina, S. Environmental Impact of the Textile and Clothing Industry: What Consumers Need to Know. **2019**.

133. Van Duijn, H.; Carrone, N.; Bakowska, O.; Huang, Q.; Akerboom, M.; Rademan, K.; Vellanki, D. Sorting for Circularity Europe: An Evaluation and Commercial Assessment of Textiles Waste across Europe 2022.

134. REHUBS A Joint Initiative for Industrial Upcycling of Textile Waste Streams & Circular Materials.

135. Waltmann, C.; Mills, C.E.; Wang, J.; Qiao, B.; Torkelson, J.M.; Tullman-Ercek, D.; Olvera de la Cruz, M. Functional Enzyme–Polymer Complexes. *Proceedings of the National Academy of Sciences* **2022**, *119*, e2119509119, doi:10.1073/pnas.2119509119.

136. Spani, R.C. The New Circular Economy Action Plan. *FEEM Policy Brief* **2020**.

137. Naletina, D. RECYCLING AS A CHALLENGE FOR THE FLEXIBLE PACKAGING INDUSTRY. *Journal of Economic & Social Development (1849-6628)* **2021**, *8*.

138. CHIMISSO, C. Waste Framework Directive Review Contents. **2022**.

139. Jarre, M.; Petit-Boix, A.; Priefer, C.; Meyer, R.; Leipold, S. Transforming the Bio-Based Sector towards a Circular Economy - What Can We Learn from Wood Cascading? *For Policy Econ* **2020**, *110*, 101872, doi:10.1016/J.FORPOL.2019.01.017.

140. Mair, C.; Stern, T. Cascading Utilization of Wood: A Matter of Circular Economy? *Current Forestry Reports* 2017, *3*, 281–295.

9. Annex

Table 12. Regulatory assessment criteria

Criterion	Description	Result	Value
Non-policy-driven supply and demand	The market can survive economically even without waste policies that exogenously push demand and/or supply or modify prices through, for example, taxes and subsidies.	-1. No; Regulation/Directive XX/XXXX includes an obligation to collect X separately -2. Partly; XXX Regulations support recycling -3. Yes; The market doesn´t need policies to push demand or modify prices	
Included in compliance schemes for packaging waste or extended producer responsibility schemes	The material is involved in closed-loop circular schemes (voluntary or policy target-driven) that enlarge the demand and supply and then favour the stability and growth of the SRM market.	-0. Not relevant -1. No; The material is not involved in closed-loop circular schemes -2. Partly, Only a few EU Member States have EPR schemes in place, but their introduction is planned at the EU level. -3. Yes, The material is involved in closed-loop circular schemes	
No competition from energy use	The SRM material is not subject to competing demand from energy recovery operations that can enlarge the market but (especially for a stable supply) can also displace the SRM market	-1. No; Energy recovery competes strongly with recycling. -2. Partly, Energy recovery competes with recycling -3. Yes, The SRM material is not subject to competing demand from energy recovery operations that can enlarge the market but can also displace the SRM market	

Product specifications are standardised	The SRM is subject to agreed or formal (regulatory) definitions and standards that are accepted and recognised by operators as references for contracts and transactions.	-1. No; The material doesn't have regulatory definitions and standards accepted and recognised by operators as references for contracts and transactions -2. Not for the entire family of the material (Only for certain polymers) -3. Yes, The material has regulatory definitions and standards accepted and recognised by operators as references for contracts and transactions	
No regulatory barriers to using SRMs as inputs in manufacturing	The SRM is not subject to adverse or discriminatory regulatory provisions for its use as an industrial commodity. Moreover, it is not subject to regulatory difficulties or barriers, for example in the end-of-waste process.	-1. No; The SRM suffers regulatory difficulties, barriers, uncertainties, ... -2. Partly, Unclear rules -3. Yes, The SRM is not subject to regulatory difficulties or barriers	