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European Technology Platform
for Sustainable Chemistry

Plastics Strategic Research and Innovation Agenda in a Circular Economy

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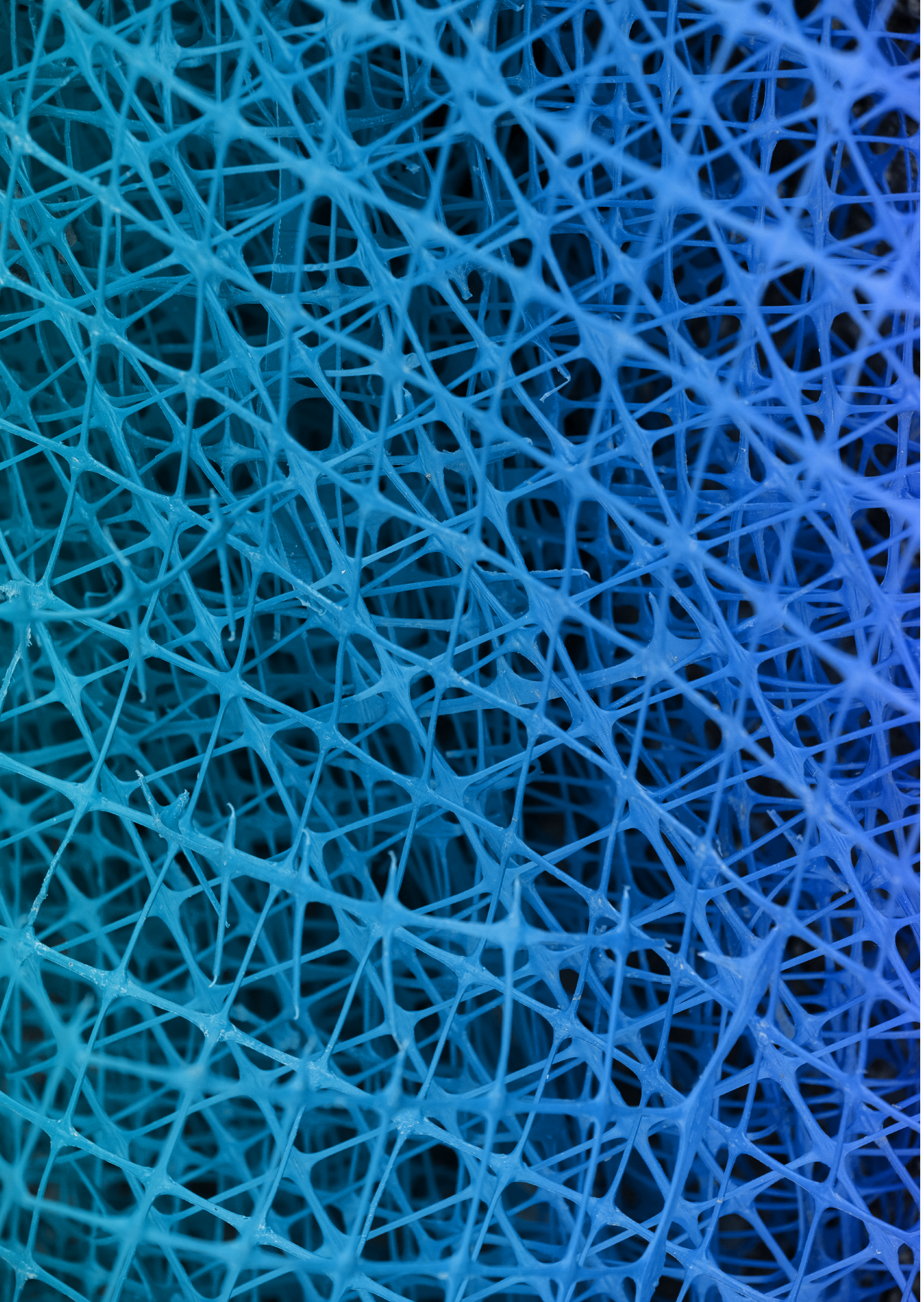
Content



Introduction

The European Commission's release of its Strategy for Plastics in a Circular Economy[1] provides a great impetus for the plastics industry to increase the circularity of a material that offers extraordinary benefits for society.

Thanks to their versatility and high resource efficiency, plastics have become key materials in strategic sectors such as packaging, building & construction, transportation, renewable energy, medical devices and even sports products, to mention but a few areas of application.

Moreover, plastics have enabled innovation in many other sectors allowing the development of products and solutions that could not exist today without these materials.

There are 60 000 companies in the European plastic industry, most of them SME's, employing over 1.5 million people and generating a turnover close to EUR 350 billion in 2016.

The EU uses about 50 million tonnes of plastics per year and it is projected that European Plastics demand will continue to grow to enable the resource efficient products needed by society. Designing mindful products with plastics and using plastics waste as a resource at the end of products' useful life are crucial elements in a circular economy.

In 2016, 27 million tonnes of plastic waste were collected in Europe of which 27% was still sent to landfill leading to a loss of valuable resources. About 8.4 million tonnes entered recycling facilities and 11.3 million tonnes were treated for energy recovery[2]. This shows there is clear room for improvement and the stakeholders behind this report envision the creation of true circularity and improved resource efficiency as a reality for plastics. In doing so, plastics will accelerate their contribution to the European Circular Economy objectives of reduced greenhouse gas emissions, higher resource efficiency and job creation.

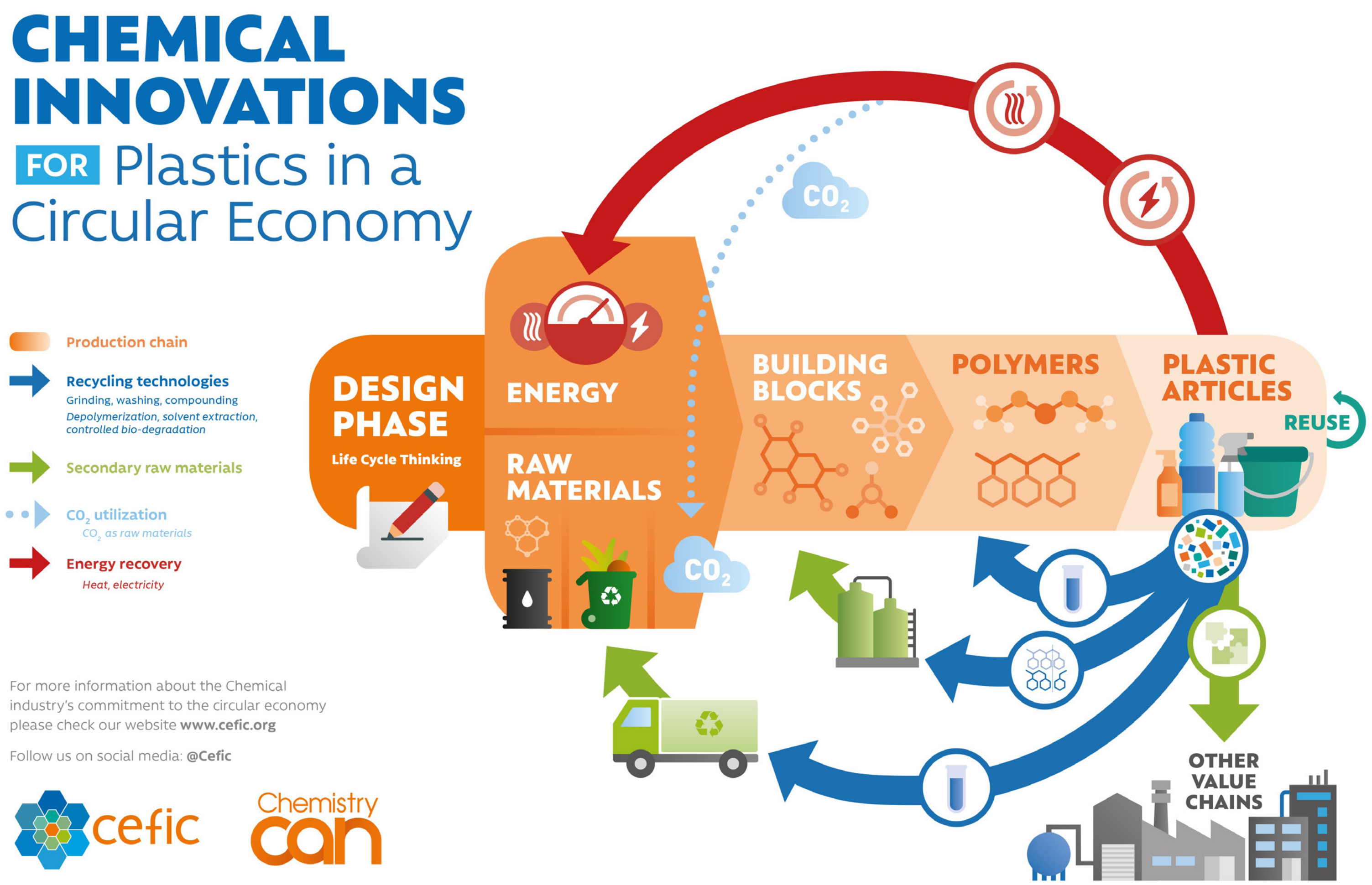
To achieve an overall increased circularity, it is important to:

- Design materials with enhanced separation and recycling properties,
- Design articles/products to encourage reuse,
- Develop repair solutions that extend the lifetime of plastic articles,
- Innovate advanced recycling technologies to increase the value retrieved from plastic waste,
- Incorporate alternative feedstocks in the production of plastics - feedstocks that take waste or by-products from other sectors and processes, such as biological feedstock from the agricultural industry, carbon-based feedstock from the chemical industry and chemical and secondary plastics from the plastic industry.

Our ultimate vision is that the carbon used in and for the production of plastics is recycled in the most resource efficient way taking all cycles into consideration as shown in the pictogram below. The digital transformation of European industry will also play a key role as an enabler to reach circular economy goals.

The Plastics Industry is committed to increase circularity and resource efficiency. This was affirmed in the industry's voluntary commitments published in January 2018[3,4].

1. http://ec.europa.eu/environment/circular-economy/pdf/plastics-strategy-brochure.pdf
2. Plastics – the Facts 2017 - PlasticsEurope.
3. The European Plastics Industry Circular Economy Voluntary Commitments (PETCORE, VINYLPLUS, ECRA and PCEP)
4. Plastics 2030, PlasticsEurope's Voluntary Commitment to increasing circularity and resource efficiency (PLASTICSEUROPE)



Source: Cefic

Innovation as a global framework will play a key role in these initiatives and go hand-in-hand with cooperation between and along the whole plastics value chain.

The complexity of the plastic value chain, due to the large number of stakeholders (producers of plastics and chemical raw materials, converters, brand-owners, retailers, actors in waste management, etc.), makes the creation of **innovation ecosystems** necessary to face the circular economy challenges that lie ahead.

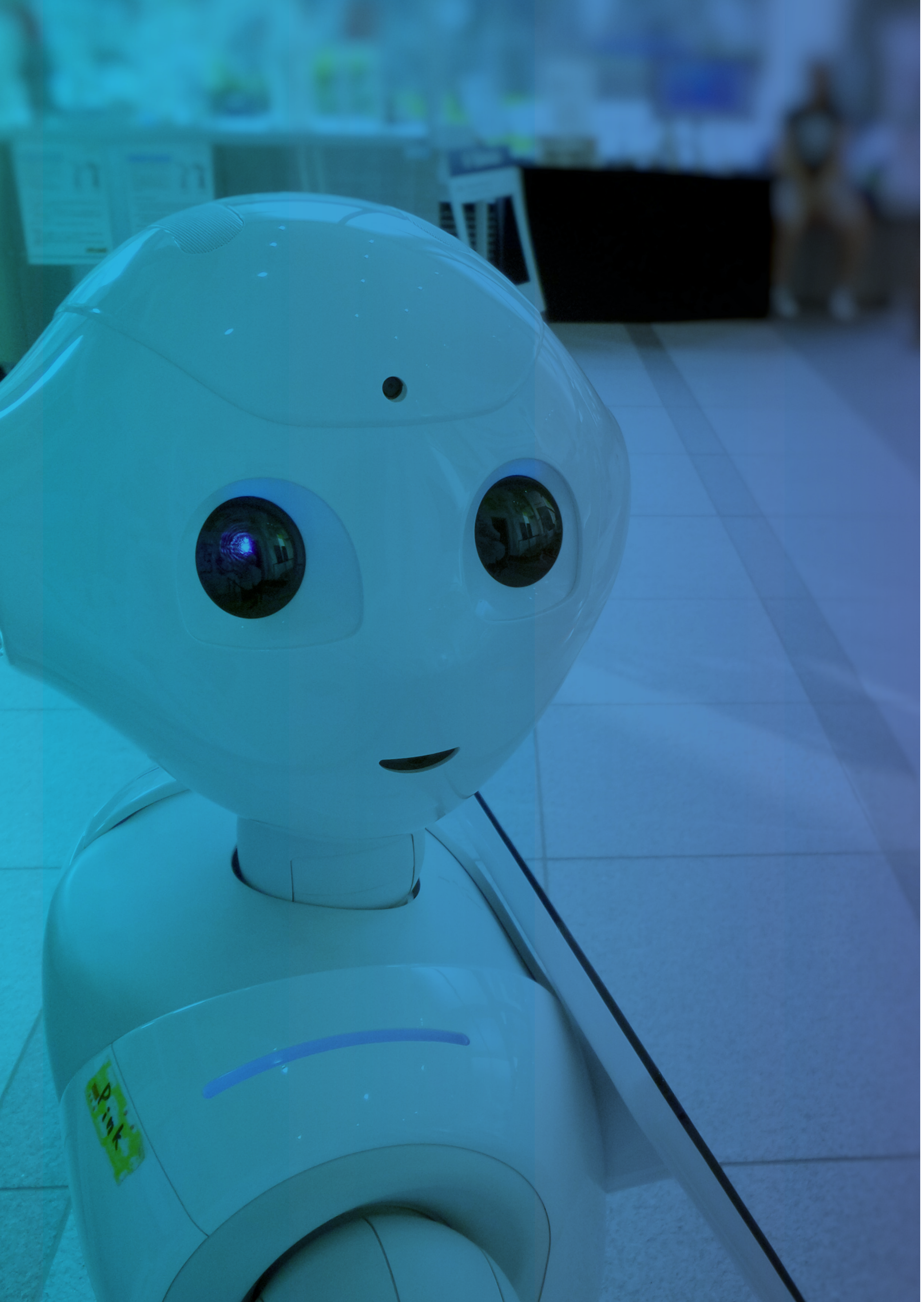
To take advantage of these ecosystems to make plastics more circular and adjusting their life cycle accordingly will require a simplification of all associated systems (business models, product design, etc.).

This report presents a shared vision and demonstrates how collaboration within the plastic value chain will be a driving force for change.

This document outlines the future research needs required to fulfill the objectives of the European Plastic Strategy. The technology solutions described are part of an integral approach to make the entire plastics production more circular.

The technology solutions for improved circularity are described in three main chapters:

Circularity by design
Circularity by recycling
Circularity by alternative feedstocks

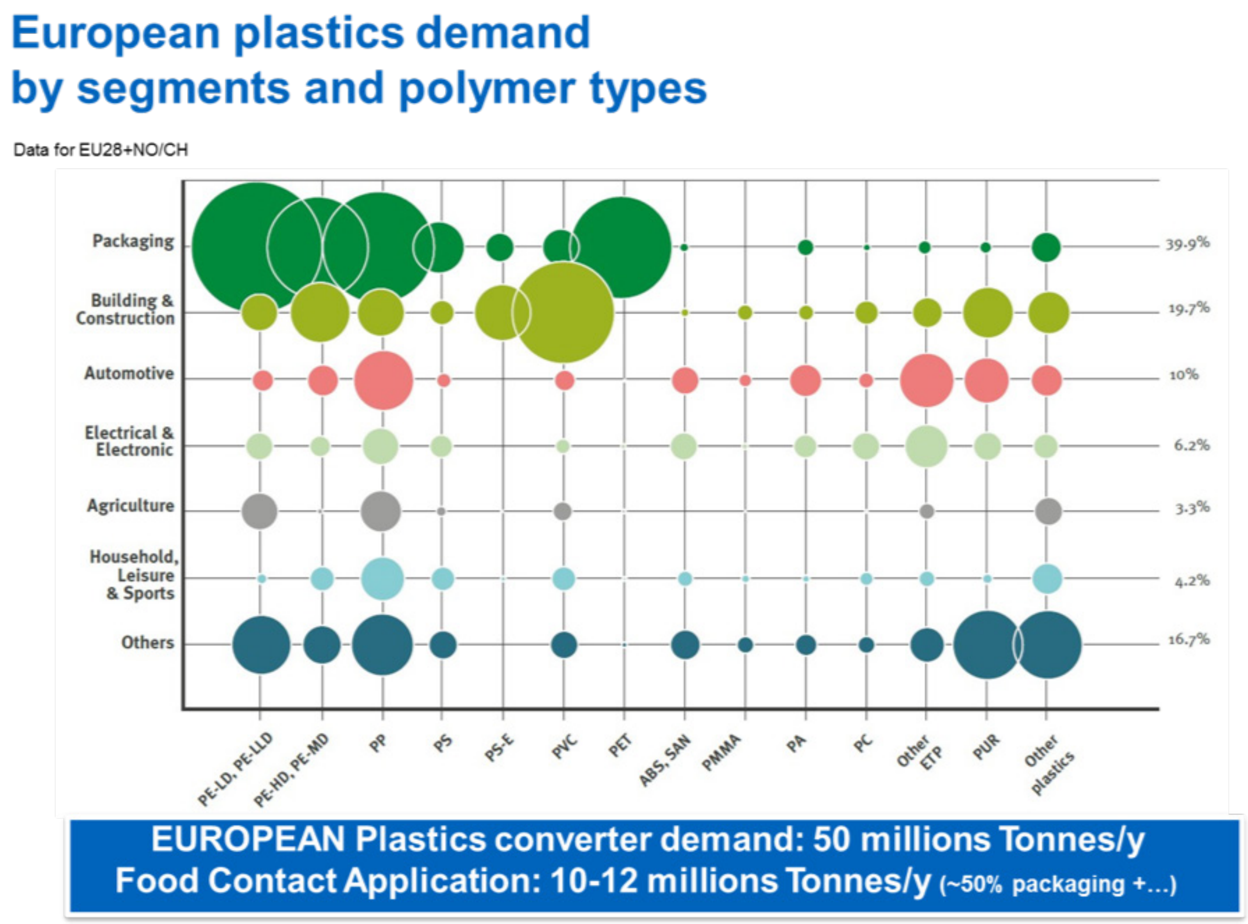


Methodology

This document was developed using input from experts involved in the plastics value chain; principally from the European Technology Platform for Sustainable Chemistry (SusChem), the European Chemical Industry Council (Cefic), the European Composites, Plastics and Polymer Processing Platform (ECP4), the European Plastics Converters (EuPC), and PlasticsEurope.

As a first step, a data input sheet was created to identify the challenges, the associated technological solutions, and the necessary innovative steps required to increase the maturity of the technological solutions to address the challenges. Input was collected by means of telephone interviews and circulation of an input sheet amongst experts. The input was classified by the different plastic value chains, the type of polymer(s) used, and the stage in the plastic's lifetime. This allowed the collection of highly granular and detailed input and ensured that the proposed solutions cover a wide range of material and application combinations that can be applied at different stages in the plastics lifecycle. The detailed input will be further developed to feed into the SusChem SIRA to be published in 2019.

Table 1: European plastics demand by segments and polymer types



Data: 2016. Sources: PlasticsEurope Market Research Group (PEMRG) / Conversio Market and Strategy GmbH

This document shows the consolidation of the detailed input and tables 3, 4 and 5, listing all relevant solutions, can be found in each of the three chapters (circularity by design, recycling and alternative feedstocks). These tables indicate:

- The relative potential impact per technology headline (low, medium or high),
- In broad terms the categories of short-term Investment needs, whether they are at Research, Pilot, Demonstration or Industrial level,
- Whether they should lead in the Horizon Europe framework programme, from 2021 onwards, to a Research and Innovation type action (RIA: project starting at TRL <4/5) or to an Innovation type action (IA: project starting at TRL>4/5).

The list of solutions is not exhaustive but it represents the major short-term priorities of the industry.

Table 2: Polymer types and value chains considered

Polymer types		Value chains
Fossil-based	**Bio-based**	
PU/PUR	PLA	Packaging
PS, PS-E, PS-EI	Starch-based	Building & Construction
PE, PE-LD, PE-LLD, PE-HD, PE-MD	PHA/PHB	Automotive
ABS-SAN	TPS	Electrical & Electronics
ABS-HIPS	PEF	Household, Leisure & Sports
PET	PBS/PBSA	Agriculture
PP	PT	
PA	Bio-PET	
PVC	Bio-PE	
PMMA	Bio-PP	
PBT	Bio-PA	
POM	Bio-PUR	
PTFE		
DCPD	**CO_2/CO-based**	
PC	PPC	
	PU	
FRP matrices	PC	
Epoxy	PEC	
PU	PE	

Circularity by Design

This section covers the technologies that can be employed at the material or article design stage to enable a circular economy based on design and simulation with advanced materials and processes. For example, the design of plastic components to facilitate dismantling and the capability to recycle the polymers. In the value chain, it is mainly the simulation, material and manufacturing steps that are the key stages to reach an optimum for circular economy by design.

1. Material design

This section describes the technologies applied at the material design phase that aim to improve its overall circularity. The technologies are categorised according to their desired path to increase circularity.

1.1. Extend lifetime

a) **Specific Challenges:** repairing and preserving polymer properties.

These technologies aim to reduce end-of-life plastic waste by extending the lifetime of polymer materials (and hence product/ article lifetime). Repairing and preserving polymer properties (e.g. self-healing polymers) are a solution in the medium to long-term.

Scope:

Several applications of polymers need to preserve their structural and physical properties for long periods of time, and often withstand extreme conditions that generate erosion and other wear mechanisms. Structural repair is a major challenge particularly for advanced composites in the aerospace industry, wind turbine and automotive applications. Different defects are initiated during manufacturing and in-service use. During manufacturing and use, delamination and matrix cracking that cannot be repaired with existing technologies can occur leading to high scrap rates of up to 20-30% depending on the part complexity. Different solutions have been demonstrated to address these specific challenges including self-healing polymers based on thermally reversible Diels-Alder reactions, disulphide-thiol exchange reactions, repair polymers based on dynamic hardeners, etc.

Further improvements are possible to develop more accurate and effective detection signals (e.g. UV, pH, temperature) to trigger the healing process when needed. Other innovative activities, such as increasing the speed of the exchange reactions through the use of linkers to develop more accurate and effective detection signals and the optimisation of novel repairing technologies based on the reshuffling of chemical bonds by applying heat and pressure, should be considered. Such innovation activities are needed to reach higher TRLs.

Technology Readiness Level

Activities should start at TRL 3 and achieve TRL 5-6 at the end of the project.

Expected Impact:

Significant reduction of the time and resources needed for material development and upscaling, should be quantified with respect to established conditions for specific market sectors, with a return on investment in less than five years. Quantifiable enhancement of the ability to control the quality and reliability of products, with consequent improvement of product lifetime and associated environmental benefits.

b) **Specific Challenges:** Improving ageing performance.

External conditions such as (extreme) temperature, pressure, UV exposure, humidity, mechanical stress and others can, over time, degrade material properties and decrease their performance. In order to increase article lifetime, it is desirable to limit the degradation due to the ageing mechanisms and improve the ageing performance. Different approaches have been developed like the addition of additives in the plastic or composites matrix and their well-controlled application in relevant areas throughout the matrix structure. To control these improvements at the nano-reinforcement and polymeric matrix interface, there is a need to improve chemical compatibility and dispersion stability as well as increasing mixing efficiency as necessary.

Scope:

Additives and nano-additives show potential for improving polymer performance by adapting each material to its specific application requirements. Replacing additives by next-generation bulk materials is a potential solution. Material properties at the nano- and microstructure level can be programmed, by changing their morphology, in order to control and adapt them to different conditions (e.g. improving barrier properties by increasing the diffusion path for gases and water, adjusting stiffness, rigidity, and sealability, etc.).

Recipe and ingredients may be optimised in order to adjust material properties to meet the requirements of specific applications and environments thereby extending its in service lifetime without undermining the efficiency and quality of the recycling process. Such an approach is relevant for both fossil-based and bio-based plastics.

Technology Readiness Level

Activities should start at TRL 4-5 and achieve TRL 6-7 at the end of the project.

Expected Impact:

At least 20% faster verification of materials performance for highly promising applications. At least 20% improvement in industrial productivity, reliability, environmental performance, and durability, and reduction of life-cycle costs for these materials.

c) **Specific Challenges:** Improving ageing performance of bio-based materials.

To improve the final properties of bio-based materials and their basic surface properties without chemical treatment and use of liquids. One solution could be based on a single-polymer approach and confined crystalline structure of PLA or PHA with low gas permeability. In particular, this could improve barrier, anti-fog, anti-fouling and antistatic surface properties of bio-based materials.

Scope:

Various approaches have already been developed like the addition of additives in the bio-based plastic or composites matrix or a good control at nanoscale of the matrix structure. Additives and also nano-additives can improve polymers performance by adapting each material to its application requirements. Replacing additives by next-generation bulk materials is another potential solution. Application of different available or emerging technologies (CVD, PVD, nanolithography, etc.) to achieve smart surface design for all types of bio-based polymers or get a good control of surface or internal polymer structure through processes. Develop active bio-based packages to meet the needs of both fresh and pre-treated food applications for specific flexible and rigid food packaging in diverse market segments. Scale up of existing laboratory level smart functionality technologies to prototype pilot scale level.

Technology Readiness Level

Activities should start at TRL 5 and achieve TRL 7 at the end of the project.

Expected Impact:

At least 20% improvement in materials performance for promising applications.

At least 20% improvement in industrial productivity, reliability, environmental performance, durability, and reduction of life-cycle costs for bio-based materials.

1.2. Decrease material usage

Technologies that aim to decrease material usage by improving required mechanical behaviour of existing materials.

a) **Specific Challenges:** Improve performance.

Ever growing demand for high performing materials and more complex products increases the need for material usage, in terms of quantity and variety.

Scope:

Composites with additional features can improve material performance by providing high strength and stiffness without undermining the aesthetical appearance of the final product. Composites materials require less material for a given functionality and have the potential to perform as well as, or better than, conventional metals decreasing the final amount of material employed.

The innovation would come from development of new precursor formulations and manufacturing technologies to reduce the cost of raw materials. The development of automated manufacturing technologies is required to reduce cycle times and cost of manufacturing. With respect to circular economy approaches, the improvement of separation between dissimilar materials and recycling properties are real needs.

Technology Readiness Level

Activities should start at TRL 5 and achieve TRL 8 at the end of the project.

Expected Impact:

At least 20% improvement in industrial productivity, reliability, environmental performance, durability, and reduction of life-cycle costs of these materials.

At least 15% improved industrial process parameters and 20% faster verification of materials performance for highly promising applications.

1.3. Improve sorting

Technologies aiming to improve the inherent sorting characteristics of polymers.

Specific Challenges:

Technologies aiming to improve the inherent sorting characteristics of polymers. The wide variety of plastics and their diversity of characteristics make the plastic sorting process very complex and inefficient, resulting in large losses of material value. The identification of different types of polymers among plastic waste is not efficient enough due to the variety of colours, properties and shapes. Multilayer materials, dark, and especially black, coloured plastics and compostable plastics are especially challenging when it comes to detection, sorting and separation.

Scope:

Today, many technologies exist to sort plastic wastes. Generally, the techniques are based on surface markings through diffraction gratings, fluorescent markers or UV markers. For example, Tracer-based sorting (TBS) is an optical technology which detects specific light signals emitted by the polymers, which have previously been exposed to a certain light source, but the cost and efficiency need to be improved. The optical response and sorting effectiveness of different marker-plastic combinations and thermal stability are some of the main bottlenecks with the recyclability of plastics containing markers. The repeatability and reproducibility need to be improved in order to increase the sorting efficiency and also the quality of the recyclable plastics.

The developed solutions can be applied to packaging as well as other applications.

Technology Readiness Level

Activities should start at TRL 3 and achieve up to TRL 8. This range is broad based on both the development of new concepts (at low TRL) and the improvement of existing ones.

Expected Impact:

Create new technologies and business opportunities for the recycling industry across Europe, especially in the area of plastics where the sorting challenge is high. Towards 100% recycled plastic after sorting stage.

Demonstrate a potential reduction in landfill waste volume by > 50%.

Meeting the EU's circular economy and environmental targets while demonstrating a clear benefit.

1.4. Improve separation

Specific Challenges:

Technologies aiming to improve the inherent separation characteristics of polymers. Multilayer or multipolymer structures are some of the plastic waste streams which need an efficient separation in order to improve the quality of recycled plastics and to decrease landfill. Multilayer polymers and composites present severe limitations for separation, due to the different properties of each component.

For example, the presence of dynamic chemical crosslinks in thermoset fibre reinforced polymer composites (TS FRP) could enable the chemical separation of the matrix from fibre reinforcement.

Scope:

Cross Linked Thermosets (CLT) and FRP composites cannot be recycled through re-melting due to their cross-linked three-dimensional chemical structure and their complex structure, respectively. Combining nucleation and low crosslinking degrees could be a way to facilitate the separation of fibres from the polymer matrix. In multilayers or multimaterials, polymers can be easily separated into relatively pure mono-material streams. Reversible adhesives have been demonstrated with different approaches (Shape Memory- and Hydrogen Bonding, with conductive nano-ferromagnetic particles, incorporating enzymes, vitrimers, etc.). Such laboratory experiments need to be scaled up and demonstrate improvements in the chemical separation process efficiency by optimising time, temperature and the type of solvents used. In order to get a high separation efficiency, it is important to get adhesion between multi-materials with high bonding and quick bond breaking/remaking capability whatever the process uses to produce the multilayer or multi-material products (extrusion, injection, etc.). The optimisation of the process and separated material for the reuse of separated resins and fibre reinforcements is crucial for the final validation of separation efficiency.

Technology Readiness Level

Activities should start at TRL 4- and achieve TRL 7 at the end of the project.

Expected Impact:

Create new technologies and business opportunities for the recycling industry across Europe, especially in the area of composites and plastics where the challenge is high; demonstrate a potential reduction in landfill waste volume by > 50%. Reduction of the carbon footprint of the corresponding products by > 30% (based on a full Life Cycle Assessment).

1.5. Increase recyclability

Technologies aiming to increase inherent recyclability of polymers.

Specific Challenges:

Recycling of multi-layer films, or recycling of waste from electrical and electronic equipment (WEEE) is difficult due to the multiple types of polymers included in such products and the difficulty in separating them. The transformation from multicomponent (multilayer or blend of polymers) compositions to one compatible multiphase mixture (which can be more easily reprocessed) by incorporating compatibilising substances is necessary.

Scope:

The development of a new generation of compatibilisers could offer a wider range of potential compatible mixtures of polymers from multicomponent products. The compatibiliser can upgrade mechanical properties and reach optimal properties of waste streams through compatibilisation of contaminant and/or different polymer phases. Also, separation of layers based on specific adhesive or additives could facilitate separation and recyclability of higher waste streams purity. Another approach for thermoset products could be based on thermal recycling processes with higher yield based on chemically modified polymers (e.g. PS), which can facilitate thermal degradation without affecting mechanical properties. The use of organic pigments can help minimise scrap/waste during thermal recycling processes.

Technology Readiness Level

Activities should start at TRL 2-5 and achieve TRL 5-8 at the end of the project.

Expected Impact:

Improvement of the recycling yield, improved purity of waste and the quality of the recyclable plastic. Increase the use of recyclable polymers in second-generation products.

1.6. Trigger biodegradability

Specific Challenges:

Conventional polymers are still predominantly used in packaging products, which due to their vast diversity, material complexity and the relatively low cost of landfill, end up not being reused nor recycled.

Biodegradable materials provide unique properties in specific applications such as the collection of food waste. For these applications, the key is to make separate collection of bio-waste. Furthermore, environmental claims regarding biodegradability or compostability should comply with appropriate standards such as ISO 18606 or EN 13432 and EN 14995.

Scope:

Compostable films can, for example, have a shelf life of one year with identical mechanical properties to non-compostable films and can be converted through extrusion. At their end of their life, they can be used for compost domestically, achieving more than 90% disintegration in less than six months. Biodegradable polymers can be produced from different bio-sources, as well as fossil sources. Different approaches towards biodegradation have a high potential such as the enzymatic approach.

The design of the raw material-bacteria final sequence is another approach, in fact some microbes can degrade plastics like PP, PE, PS to shorter hydrocarbons. In addition, efficiency of microbial plastic degradation can be enhanced with metabolic engineering. Whatever the solution, there is a need to get good repeatability, purity of monomer, duration, and thermal stability. In fact, more progress is necessary for the various bio additives to improve their properties and control their biodegradation which also needs to comply with internationally recognised biodegradability standards.

Technology Readiness Level

Activities should start at TRL 4 and achieve TRL 7 at the end of the project.

Expected Impact:

Reduce the environmental footprint associated with the end-of-life phase of developed packaging products by at least 30 % compared with existing products for similar applications.
Improve sustainability performance (in terms of biodegradability, compostability or recyclability) compared with existing plastics.
Develop at least two applications utilising 'outperforming' biodegradable polymers, with improved properties compared to the current alternatives based on fossil-based counterparts.

2. Article Design

This section elaborates on the technologies applied at the product design phase that aim to improve the overall material circularity. The technologies are categorised according to the desired way they aim to increase circularity.

2.1. Design for dismantling

Specific Challenge:

Integrate environmental criteria in product design in order to minimise material use. Design parts considering weight and multi-material optimisation (i.e. use the right material at the right place and optimise its form to limit weight, etc.). Technologies aiming to ease dismantling of products containing plastic with the ultimate goal of increasing the volume and purity of the collected and sorted plastic waste, resulting in higher quantities and quality of the recycled or reused material.

Scope:

It is common that component parts of the same product have different characteristics and lifetimes. The lack of dismantling considerations at the design stage results in long-lasting materials being discarded before reaching their optimal end-of-life.

Coupled with the growing complexity of products, materials that otherwise are easily recyclable lose most of their potential quality due to the inability to separate mono-material parts from each other. Design product parts to incorporate adhesives that can be triggered for easy disassembly, such as reversible adhesives based on Diels-Alder reaction and dithiol exchange reactions.

Technology Readiness Level

Activities should start at TRL 4- and achieve TRL 7 at the end of the project.

Expected Impact:

Create new technologies and business opportunities for the recycling industry across Europe, especially in the area of composites and plastics where the challenge is high. Proposals should prove that the target products are recyclable or compostable in various environments to reduce their overall environmental footprint. This will make their production and use more circular.

2.2. Decrease material usage

Specific Challenge:

Multi-material design and product complexity. The growing complexity of products, together with the wide variety of existing polymers, boosts the use of multi-material design in single applications.

Scope:

Replace multilayer structures by compounds; materials with targeted thickness to replace multiple material use. Push and facilitate the use of composite solutions based on polymers, versus traditional solutions (e.g. based on metals). Design parts considering weight and multi-material optimisation (use the right material at the right place and optimise its form to limit weight, maximise resistance, etc.).

Integrate environmental criteria in packaging design in order to minimise material use (e.g. mono-material design) whilst simultaneously offering the same or better functionality.

Technology Readiness Level

Activities should start at TRL 4 and achieve TRL 8 at the end of the project.

Expected Impact:

Reduce the environmental footprint associated with the end-of-life phase of developed packaging products by at least 30 % compared with existing products for similar applications. Produce multifunctional product with a minimum of multilayer/ multimaterial structures.

2.3. Digital design for reuse

Specific Challenge:

Often, the primary factors used for the design of an article are performance cost and safety, without considering the use and reuse of material. In many cases, the lifespan of the polymers used is longer than the lifespan of the application they are used for (e.g. packaging, transport with hydrogen fuel tanks in fuel cell vehicles, etc.).

When the applications reach their end-of-life (EOL), they usually end up in landfill, although the polymers could be reused for several more years. Most of the time, EOL considerations and the possibility for re-use are not taken into account during the article design phase. It is necessary to design the product to improve the performance of the final product and the process technologies (extrusion, compound, etc.) for all polymers in order to avoid/decrease degradation of the polymer matrix. Remanufacturing processes for polymers need to be improved in order to make it more attractive to remanufacture polymer parts to get high quality and high-performance polymer products.

Scope:

Integrate environmental criteria in material design in order to take into account its reuse. Improvement of material durability is crucial for a longer lifetime. Existing extrusion and compounding technologies or different new generation of processes can provide a quick and affordable solution for remanufacturing parts (e.g. additive manufacturing, multi-manifold die, etc.). Hybrid technology processes with specific positioning could be one such new generation of process. The goal of the advanced process chain is to avoid the degradation of the polymer matrix and to use the right amount of polymer. Finite element analysis for modelling of product end use performance is also a part of this design chain. Digital technologies are also important from the design stage to the identification of the polymer product before reuse. Define standards for common interfaces of articles so that parts can be re-used. In order to get the best capability of reuse for polymer products, a sustainable business model needs to be specified towards the use of consolidated blockchains.

Technology Readiness Level

Activities should start at TRL 5 and achieve TRL 7 at the end of the project

Expected Impact:

Reduce the environmental footprint associated with the end-of-life phase of developed products by at least 30% compared with existing products for similar applications. Demonstrate a potential reduction in landfill waste volume by > 50%.

2.4. Use of digital techniques for design of bio-based materials

Specific challenge:

Bio-based raw material batches usually vary with respect to their chemical and physical properties. These fluctuating properties have an influence on process parameters and final polymer characteristics having impact on properties that are important for use, lifetime and recycling. Therefore, fluctuations must be taken into account when setting up protocols for the adjustment of processing parameters in operations like polymerisation plants and polymer processing (e.g. extrusion, injection, etc.).

Scope:

New tools help to control and adjust process parameters online when bio-based materials are used as feedstock for polymerisation processes. These predictive control mechanisms permanently track the raw material composition and properties and adjust process parameters to compensate for fluctuating input parameters. These advanced digital tools allow tailoring of polymer composition and architecture with respect to application properties including durability, biodegradability and recyclability. These tools can be applied for pure polymers as well as blends and allow for predictive calculations of their performance.

Technology Readiness Level

Activities should start at TRL 5 and achieve TRL 7 at the end of the project.

Table 3: Circularity by Design

Material design (chemical industry gate)

Challenges	Solutions	Type of Polymer	Value chains	Impact	Short term Investment needs 2018/2020	Type of action from 2021 (Horizon Europe)
Extend life-time				**High**		
Challenge 1: Repairing and preserving polymer properties	Self-healing polymers based on thermally reversible Diels-Alder reaction	Epoxy, PE, PU,	All		Research	IA
	Self-healing polymers based on disulphide-thiol exchange reactions	N/A	All		Research	IA
	Repairable polymers based on dynamic hardeners	Epoxy	All		Research	RIA
	Self-healing materials based on polyrotaxanes	N/A	All		Research	RIA
Challenge 2: Improve ageing performance	Programmable microstructure	All	All		Research	RIA
	Nano-additives coupled with "single-polymers"	PS, SAN, ABS	Packaging (can be extended to All)		Research	RIA
	Sustainable additives	All	All		Research	RIA
	New generation additives as UV stabilisers	PE-LD, PE-LLD, PE-HD, PE-MD	Agriculture		Research	IA
	Treatment of bio-based materials in atmospheric conditions	Bio-based	All		Pilot/ Demonstration	IA
	Bio-based material with improved barrier properties	Bio-based	All		Research	IA
	Nano-reinforcements	All	All		Pilot	IA
	Humectant and dispersant additives as resin nano-reinforcement	FRP	All		Pilot/ Demonstration	IA
Decrease material usage				**Low**		
Challenge: Improve performance	Composite materials	FRP			Pilot/ Demonstration	IA

IA = Innovation Action
RIA = Research Innovation Action

Material design (chemical industry gate)

Challenges	Solutions	Type of Polymer	Value chains	Impact	Short term Investment needs 2018/2020	Type of action from 2021 (Horizon Europe)
Improve sorting				**Medium**		
Challenge: Programming materials for smart sorting	Tracer-based sorting (TBS)	All	Packaging, Household Leisure & Sports		Research	RIA
	Markers for UV tracing	PET, PE, PHA/ PHB	Packaging		Research/Pilot	IA
	Light barrier without mineral for white and cream packaging	PET	Packaging		Research	RIA
	Black sortable colourants to support NIR sorting	PET, PP, PS, PE	Packaging		Demonstration/ Industrial/first of a kind	IA
Improve separation				**Medium**		
Challenge: Improve separation capacity of multi-layer polymers and composites	Reversible cross-linking/ cross-linked polymers	PE-LD, PE-LLD, PE-HD, PE-MD, PET, PS, PS-E, Epoxy, PU, FRP	All		Research	RIA
	Bio-degradable bond layers	PE-LD, PE-HD, OPAI	Packaging		Research	IA
	Reversible adhesives for multi-layer film	All	Packaging		Research	IA
	Combine nucleation and low crosslinking degrees	PA, PP, PBT	Automotive, Electrical & Electronics		Research	IA
	Organic linked polymers	PS, ABS/SAN, FRP	Automotive, Electrical & Electronics		Research	IA
	Vitrimers	PE, PP, PS, FRP	All		Research	IA
	Water-soluble adhesives	All	All		Research	IA

IA = Innovation Action
RIA = Research Innovation Action

Material design (chemical industry gate)

Challenges	Solutions	Type of Polymer	Value chains	Impact	Short term Investment needs 2018/2020	Type of action from 2021 (Horizon Europe)
Increase recyclability				**High**		
Challenge 1: Recycling of multi-layer films	Compatibilisers to improve recyclability of multi-layer articles	PE, PA, PP	Packaging		Pilot/ Demonstration	IA
	Compatibilisers for mechanical recycling	All	All		Research/Pilot	IA
Challenge 2: Improve yield through thermal recycling	Chemically modified polystyrene	PS	All		Research	IA
	Organic pigments	PS, SAN/ABS	Automotive, Electrical & Electronics		Research	RIA
Challenge 3: Recycling of electrical & electronic waste	Compatibilisers to decrease deterioration of recycled blends	All	Electrical & Electronics		Research	RIA
Trigger biodegradability				**Medium**		
Challenge 1: Adequacy of polymer properties to their environment	Seawater bio-degradable polymers	PLA, PHA	Packaging, Household Leisure & Sports		Research	IA
	Bio-polyester and starch mixed polymer	Starch-blends, TPS, PLA, PHA, PBS	Packaging		Demonstration/ Industrial/first of a kind	IA
	Enzymatic solution	PET,PLA	Packaging		Research/Pilot	IA
	Design of the raw material-bacteria-final sequence	PP, PS, PET, PE-LD, PE-LLD, PE-HD, PE-MD	All		Research	RIA
	Develop new intrinsically biodegradable polymers	All	All		Research	RIA
Challenge 2: Adjustment of plastic to realistic degradation conditions	Incorporation of functionalities into the polymer backbone	All	All		Research	RIA
Challenge 3: Avoiding methane release					Research	RIA

IA = Innovation Action
RIA = Research Innovation Action

Article design (Plastic converters gate)

Challenges	Solutions	Type of Polymer	Value chains	Impact	Short term Investment needs 2018/2020	Type of action from 2021 (Horizon Europe)
Design for dismantling		All		**Medium**		
Challenge: Lack of dismantling or separation considerations	Chemical modifications of the adhesives and/or the primers	All	All		Pilot/ Demonstration	IA
	Mechanical dismantling	All	All		Pilot/ Demonstration	IA
	Barrier adhesives	All	All		Pilot/ Demonstration	IA
	Surlyn® sealant polymers	PE	All		Pilot/ Demonstration	IA
Decrease material usage				**Medium**		
Challenge: Multi-material design and product complexity	Eco-design considerations	PET, PE, PP	All		Research	IA
	Mono-layer packaging	All	Packaging		Pilot/ Demonstration	IA
	Machine Direction Orientation (MDO) and Biaxial Oriented Polyethylene (BOPE)	PE-LD, PE-LLD, PE-HD, PE-MD	All		Pilot/ Demonstration	IA
	Topological optimisation algorithms	All	All		Research	RIA

IA = Innovation Action
RIA = Research Innovation Action

Article design (Plastic converters gate)

Challenges	Solutions	Type of Polymer	Value chains	Impact	Short term Investment needs 2018/2020	Type of action from 2021 (Horizon Europe)
Digital design for reuse				**Medium**		
Challenge 1: Lack of EOL considerations	Eco-design considerations	PET, PE, PP	All			CSA
	Define article common interface standards	All	All			CSA
Challenge 2: Polymer matrix degradation	Customisation of conventional extrusion and compounding technologies	All	All		Research/Pilot	IA
Challenge 3: High replacement rate	Additive manufacturing	All	All		Research	RIA
Use of digital techniques for design of bio-based materials				**Medium**		
Challenge: Counterbalancing fluctuations of bio-based raw materials fluctuations	New tools for adaptive processes	Bio-based	All		Pilot/ Demonstration	IA

IA = Innovation Action
RIA = Research Innovation Action
CSA = Coordination Support Action

Circularity by Recycling

1. Plastic stream preparation (waste pre-treatment)

Specific Challenges:

Plastic articles to be recycled contain solid and liquid contaminants that result from their specific use and history. These contaminants can significantly affect the quality of the recycling output and are not easily removable. In addition, they may convey to the plastics notable odours that do not modify their physical or chemical properties but can make the recycled materials unfit for some specific uses. The contamination of used farm films is a typical example. In mulching and semi-forcing techniques, the contamination of the plastic films can represent up to 70% of the volume collected leading to significant additional costs in terms of recovery operations and treatment. In the specific case of plastics used in packaging, an additional challenge is the removal of the inks which are often directly printed on the polymer films. Removal of these inks is difficult, costly and energy intensive. As a result, plastic waste with printed inks are often recycled 'as is' and used in lower value products such as plastic shopping bags. To decrease this value loss, cost and energy efficient technologies for ink removal need to be developed.

Scope:

Solutions applied through continuous processes are especially attractive. For example, the use of solvating fluids during continuous extrusion treats flowable polymer masses by solvating and extracting organic, and especially non-volatile, contaminants from the polymer mass.

The efficacy of such approaches can be enhanced by employing sensors to detect and remove contaminants with different natures (stones, particles, additives) and sizes. The development of sensors with higher detection/precision and lower cost would allow a better treatment of the films and a higher quality of the final recycled materials. As far as the removal of odour or ink is concerned, techniques like supercritical extraction, friendly oxidant water-based treatments, or biological treatments are especially attractive. But their implementation still requires further developments to reduce their respective cost and their need for solvents.

Technology Readiness Level

Activities should start at TRL 5 and achieve TRL 7/8 at the end of the project.

Expected Impact:

Meeting the EU's circular economy and environmental targets while demonstrating a clear benefit, i.e. more efficient or economic than the state-of-the-art processes to enable market uptake in the short to medium term.

Reduction of the carbon footprint of the corresponding products by > 30% (based on a full Life Cycle Assessment).

Demonstrate a potential reduction in landfill waste volume by > 50%.

2. Sorting and separation

Specific Challenges:

The composition of the waste streams of polymer articles can vary from a stream composed solely of rigid bottles (mainly PET and PE) to streams containing additional trays, pots and films, with a wide range of different polymers. Rigid plastics can contain films which are often multi-layered, and hence difficult to separate. Bottles can be covered in PVC sleeve labels, or PET grade materials need to be separated from bottles and trays. Furthermore, applications polymers are often mixed with other materials (e.g. wood, metals, oil, etc.) and can contain legacy additives, such as brominated flame retardants (BrFR) and also organic additives such as plasticisers and dyes for which sorting and separation is difficult. In order to recycle these streams efficiently, the sorting of polymer articles by their constituent materials is of primary importance. This sorting ensures a minimum of waste and a high quality and high purity end product. This sorting is particularly tedious for small or light plastic items due to their specific geometry, morphology, and low weight. The two main routes currently employed, namely wet and dry sorting, still require further technical enhancements and cost reduction to ensure a wide deployment and an increase in the overall recovery yield of plastics. Special attention should be given to both the construction and the packaging sector as well as to bio-based polymers for which the current level of recycling is not as high as for fossil-based polymers due to the lower market volumes.
The final goal of recycling being to reduce the environmental impact, the solutions developed should avoid using consumables, which generate a negative impact on the environment.

Scope:

In the case of wet sorting, approaches like hydrocyclone and floatation still require further developments to i) strongly reduce their prohibitive cost (for hydrocyclone) and ii) offer a better selectivity on light polymers and polymers having the same density (for floatation). Closed loop processes to eliminate contaminants, best sorting for higher quality batches together with selective precipitation should be considered.

In the case of dry sorting:

- Polymer identification methods based on optical spectroscopies like Visible (VIS), Near Infrared (NIR) and RAMAN spectroscopies as well as Mid Infrared Thermography (MIR-T) and Laser-Induced Breakdown Spectroscopy (LIBS) would benefit from improvement in optical sensors. A better spatial recognition would allow automation of sorting at higher speeds and a higher accuracy (with lower detection limits) and would permit identification of legacy additives (like brominates) at lower concentrations and also organic additives.

- X-ray based techniques like X-Ray transmission imaging (XRT) and Energy Dispersive X-ray fluorescence (XRF) could be applied to smaller recycling units if their cost were reduced. Moreover, it would be beneficial to increase the detection capabilities of these tools in order to identify a wider range of additives and increase the speed of sorting.
- Terahertz spectroscopy offers interesting features, although the plastic optical recognition needs some further improvement.
- When tracers are used, fast and low-cost detection techniques to identify precisely the articles containing the said tracer should be developed up-front.

All these techniques should be coupled to enhanced sorting mechanisms (air valves, robotic handling), and should be tested at pilot scale. Developing Artificial Intelligence (AI) algorithms to reproduce human recognition capabilities could result in the development and use of AI robots to replace hand pickers. For all these solutions, Life Cycle Assessment (LCA) and Life Cycle Costs (LCC) should be considered thoroughly to evaluate the performance of the solutions.

Technology Readiness Level

Activities should start at TRL 5 and achieve TRL 7/8 at the end of the project, although some developments are, for the time being, at lower TRL in the most novel fields (e.g. identification of organic legacy additives at TRL 1 or 2).

Expected Impact:

At least 20% improvement in industrial productivity, reliability, environmental performance, durability, and reduction of life-cycle costs of these materials. Demonstrate a potential reduction in landfill waste volume.

2.1. Plastic waste preparation

Specific Challenges:

The separation of the various polymers comprised in a stack is often difficult and still needs to be performed manually most of the time. Especially after grinding, it is even more difficult to separate polymers, which results in contaminated input streams in the recycling process. Ensuring high purity and high value recyclate requires the separation of polymers in the stack in order to allow a proper sorting of the materials.

Scope:

The development of integrated solutions for grinding machinery with thermal, chemical, and magnetic separation should be considered and tested in pilot lines. The increase of production volume of the mills using cold base technology could offer some leverage on the overall energy consumption of the mills and balance of systems material flow. In addition, the use of detection systems for ground particles and agglomerates in order to better separate coarse particles and return them to the mill should be investigated. Use of supercritical liquid could permit separation of polymers in a stack in an efficient manner.

Technology Readiness Level

Activities should start at TRL 5 and achieve TRL 7 at the end of the project.

Expected Impact:

Meeting the EU's circular economy and environmental targets while demonstrating a clear benefit, i.e. more efficient or economic than the state of the art in order to enable market uptake in the short to medium term.

At least 20% improvement in industrial productivity, reliability, environmental performance, durability, and reduction of life-cycle costs of these materials demonstrate a potential reduction in landfill waste volume.

3. Recycling

3.1. Mechanical recycling

Specific Challenges:

Even with super-precise selection and sorting methods, polymer streams will often consist of a mix of different grades of polymers. Mechanical recycling allows the production of decently clean and defined materials without chemical treatment. Recyclability of FRP articles is however more difficult, usually shows low yield (particularly for the matrix), and fibres are significantly degraded, resulting in secondary use in lower value applications after each lifecycle.

Scope:

Advanced mechanical recycling techniques could be enhanced by developing:

- Stable reagents for high temperature processing by means of twin screw extruders/compounding to permit the re-introduction in the value chain of cross-linked polymers that cannot be reprocessed, under normal conditions.
- New mechanical methods to break the chemical bonds by using Twin screw extruders with the combination of high shear and high energy sources (radiation).
- New chemical compounds to enhance this process to be added in combination with physical methods.
- New mixers based on extensional flow (specific reactor) to improve dispersion and distribution quality for a wide range of viscosity ratios and avoiding thermal degradation.
- Fibre functionalisation and reactive compatibilisation extrusion.
- Reactive extrusion process to improve adhesion between the recycled fibre and polymer matrix (compatibilisation).

Technology Readiness Level

Activities should start at TRL 4 and achieve TRL 7 at the end of the project.

Expected Impact:

Improve the industrial productivity, reliability, environmental performance, durability, and reduction of life-cycle costs of these materials Demonstrate a potential reduction in landfill waste volume.

At least 15% improved industrial process parameters and 20% faster verification of materials performance for highly promising applications.

3.2. Chemical recycling

Specific Challenges:

Post-consumer waste is often not completely clean and contains impurities, colour pigments, or legacy hazardous additives such as DEHP and Pb. This generates an issue with post-recycling output, as these impurities are typically diluted and not completely removed, which creates restrictions on the sectors that the secondary material can be used in.

Scope:

Techniques to remove contaminants, and especially colour pigments in packaging materials, should be developed, for example, the employment of smart solvent combinations to convert coloured polymers back to neat colourless materials. Chemical recycling solutions that can lead to pure starting materials to produce new plastics should be researched actively.

Technology Readiness Level

Activities should start at TRL 3 and achieve TRL 6 at the end of the project.

Expected Impact:

Improve the industrial productivity, environmental performance, and reduction of life-cycle costs of these materials demonstrate a potential reduction in landfill waste volume.

At least 20% faster verification of materials performance for promising applications.

3.3. Thermal and thermochemical recycling

Specific Challenges:

Thermal-based processes for molecular chain-cutting systems are highly energy intensive, and, in some cases, they degrade the surface of the recycled material. The addition of chemical processes can enhance the overall process and provide a better alternative. However, issues of high cost of utilities (steam, electric power, water), low yields, and low-quality of the final product need to be addressed in order to make it more financially, industrially and environmentally attractive. The main outcome of the process is an oily liquid (synthetic crude oil), which can be upgraded into raw materials for chemicals and materials. The composition of the liquid varies depending on the input waste. Some purification technologies to remove hazardous chemicals exist and new ones are under development. Chemical recycling could be applied to many plastics streams which are not suitable for mechanical recycling. With increased chemical recycling the prices of petrochemicals and plastics could be decoupled from crude oil prices.

Scope:

Advanced thermochemical recycling processes should be investigated including:

- Chemical recovery through depolymerisation process able to handle varying input material qualities. This would require to i) develop suitable catalysts to increase reaction speed, steadiness, and ease, ii) reduce the overall process energy consumption, iii) reduce water usage of the process, and iv) accelerate adoption in the market (e.g. pilot plants).
- The combination of solvolysis with a microwave energy system, to decrease energy consumption and speed up the solvolysis process. The microwave technology should be especially increased in the presence of impurities.
- Gasification (possibly combined with biological and chemical post-treatment). The main outcome of the gasification process is syngas (gas mixture of carbon monoxide + hydrogen), which can, after purification, be used as raw material for chemicals and materials (conversion of syngas to methanol integrated in the process to obtain green hydrogen, integration in cogeneration to obtain renewable electric energy etc.). With further purification technologies it is possible to remove hazardous chemicals from the syngas.
- ICCP technology (Integrated Cascading Catalytic Pyrolysis), which maximises product value with high BTX and aromatics yields, while being energy positive (overall heat generation).
- Synthetic biological processes (engineered, whole-cell bacterial catalysts) to depolymerise back to monomers.
- Co-pyrolysis of plastic wastes with other wastes (e.g. cotton, organic materials with high content aromatics, etc.) to obtain new chemical intermediates.

A study should be performed, mapping the different waste streams available in Europe and how they can be adapted and fed into existing refineries and processes.

Technology Readiness Level

Activities should start at TRL 4 and achieve TRL 6/7 at the end of the project.

Expected Impact:

Improve the industrial productivity, environmental performance, and reduction of life-cycle costs of these materials Demonstrate a potential reduction in landfill waste volume.

At least 20% faster verification of materials performance for different applications.

3.4. Recycling multi-layers/ compounds

Specific Challenges:

Films with multiple layers made of different polymer types are typically difficult to separate. This creates an issue at the recycling stage, as polymer types used for the different layers are not always compatible. In addition, the interaction of filling goods (food) with the packaging multi-layer containers often results in contamination degradation of the polymers. These articles also often contain additional pigments, functional fillers, silicon layers, or adhesive materials, which makes recycling even more difficult, as the different polymers and additives need to be separated before the recycling output can be used again, especially for food and medical applications.

Scope:

Efficient recycling of such multi-layer compounds need further development. The enhancement of approaches like immersion in chemical solutions for separation and catalytic depolymerisation processes require better understanding of key parameters like processing conditions, the nature of the polymers treated, the nature of the potential contaminants, etc. In addition, scale up from lab results to pre-pilot or pilot lines should be performed.

Technology Readiness Level

Activities should start at TRL 3 and achieve TRL 6 at the end of the project.

Expected Impact:

Demonstrate a potential reduction in landfill waste volume by > 50%.

Create new technologies and business opportunities for the recycling industry across Europe, especially in the area of plastics where the challenge is high.

Reduce the environmental footprint associated with the end-of-life phase of developed packaging products by at least 30 % compared with existing products for similar applications.

4. Post-processing

Specific Challenges:

After recycling, polymeric materials can still contain contamination residues of either molecular or elemental nature. This is especially true for the recycling of polymer articles that have been manufactured under older standards using additives that subsequently have been prohibited or face future prohibition, e.g. hexabromocyclododecane (HBCD). Polymers face limits on the number of times they may be recycled without a loss in properties, e.g. clarity, strength, etc. Further work is required to extend the number of times polymers can be maintained in the recycling loop and further recycled as feedstock for the production of new polymers when mechanical recycling is no longer feasible.

Scope:

Innovation steps in the post processing methods to increase the final quality of the recyclate could include:

- Developing an EFSA or FDA approved technology to decontaminate polyolefins in order to recover the food contact status after treatment similar to existing technologies for PET (Polymer PE-LD/PE-LLD; PE-HD/PE-MD) and Flexible Film (Blown or cast).
- Developing new, versatile, conformable and low-cost processing technologies to prevent the release of contaminants through barriers/ encapsulation (any polymer especially non-glassy examples such as soft PVC), however the exact development may be polymer specific.
- Identifying or optimising property booster, modifier or compatibiliser.
- Improving the additive package of the polyethylene to minimise degradation of polymer during processing in recycling steps.
- POF property enhancers (impact modifiers, compatibilisers and coupling agents) to enhance the properties of recyclates, Develop specific compatibilisers with a high number of active sites.
- Development of reactive compatibilisation processes by twin screw extruders.

Technology Readiness Level

Activities should start at TRL 5 and achieve TRL 7 at the end of the project.

Expected Impact:

Create new technologies and business opportunities for the recycling industry across Europe, especially in the area of plastics where the challenge is high.

Reduce the environmental footprint associated with the end-of-life phase of developed packaging products by at least 30 % compared with existing products for similar applications.

Table 4: Circularity by Recycling

	Challenges	Solutions	Type of Polymer	Value chains	Impact	Short term Investment needs 2018/2020	Type of action from 2021 (Horizon Europe)
Sorting and Separation	**Plastic stream preparation**				**High**		
	Challenge 1: Removal of contaminants from plastic articles	Solvating fluid treatment during continuous extrusion to treat flowable polymer masses	All	All		Pilot/ Demonstration	IA
		Use of sensors	PE-LD, PE-LLD, PE-HD, PE-MD	Agriculture		Pilot/ Demonstration	IA
	Challenge 2: Removal of ink	De-inking	PE-LD, PE-HD, PP, PET,PVC	Packaging, building & construction		Pilot/ Demonstration	IA
	Challenge 3: Removal of odour	Supercritical fluid extraction (SFE) such as CO_2	PP, PE-LD, PE-LLD, PE-HD, PE-MD, PVC, PET, PUR, PS, PS-E	Packaging, building & construction		Pilot/ Demonstration	IA
		Friendly oxidants water-based treatments	PP, PE-LD, PE-LLD, PE-HD, PE-MD, PVC, PET, PUR, PS, PS-E	Packaging, building & construction		Pilot/ Demonstration	IA
	Wet sorting				**Medium**		
	Challenge 1: Separation of light or similar plastics	Hydrocyclone	All	Packaging		Demonstration/ Industrial/first of a kind	IA
		Floatation	All	Packaging		Demonstration/ Industrial/first of a kind	IA
		Polymer tracing (TRA)	All	Packaging		Pilot/ Demonstration	IA
		Magnetic Density Sorting (MDS)	PP, PE-LD, PE-LLD. PE-HD, PE-MD, PVC, PET, PUR, PS, PS-E	All		Pilot/ Demonstration	IA
	Challenge 2: Sorting of waste while reducing environmental impact of consumables	Closed loop process to eliminate contaminants	PP, PE-LD, PE-LLD, PE-HD, PE-MD, PVC, PET, PUR, PS, PS-EI	All		Pilot/ Demonstration	IA

IA = Innovation Action
RIA = Research Innovation Action

	Challenges	Solutions	Type of Polymer	Value chains	Impact	Short term Investment needs 2018/2020	Type of action from 2021 (Horizon Europe)
Sorting and Separation	**Dry sorting**				**Medium**		
	Challenge 1: Recovery of black polymers	RAMAN spectroscopy	ABS, PP, PC, PS, PE-HD, PA, PVC, PET	Automotive, Electrical & Electronic, Packaging		Pilot/ Demonstration	IA
		XRF, XRT	ABS/HIPS, PP, PC, PS, PE-HD, PA, PMMA, PVC, PET	Automotive, Electrical & Electronic, Packaging		Demonstration/ Industrial/first of a kind	IA
		Laser Induced Breakdown Spectroscopy – LIBS (high-performance online analysis system for industrial recycling)	ABS/HIPS, PP, PC, PS, PE-HD, PA, PMMA, PVC, PET	Automotive, Electrical & Electronic		Pilot/ Demonstration	IA
		Mid-infrared spectroscopy (MIR spectro)	POs, PVC	Automotive, Electrical & Electronic		Pilot/ Demonstration	IA
	Challenge 2: Sorting of packaging articles	Optical sorting (NIR, VIS)	All	Packaging		Research/Pilot	IA
	Challenge 3: Increase recovery of plastics from construction sector	Optical sorting (NIR, VIS)	All	Building & construction		Research/Pilot	IA
	Challenge 4: Identify additives of very high concern in older (legacy) plastic applications	LIBS	All	Electrical & Electronic		Research	RIA
		Laser sorting	All	All		Pilot/ Demonstration	IA
	Challenge 5: Inhomogeneity of waste streams	Combination of Near Infrared Technology (NIR), Visible sorting (VIS) and Mid-infrared thermography (MIR-T)	All	Packaging, Household, Leisure & Sports		Pilot	IA
		Artificial intelligence algorithms	All	All		Pilot/ Demonstration	IA
		Tera Hz	PHA/PHB?	All		Research/Pilot	IA
	Challenge 6: Sorting of bio-based polymers	NIR sorting	Bio-based	All		Research/Pilot	IA

IA = Innovation Action
RIA = Research Innovation Action

	Challenges	Solutions	Type of Polymer	Value chains	Impact	Short term Investment needs 2018/2020	Type of action from 2021 (Horizon Europe)
Sorting and Separation	**Plastic waste preparation**				**Medium**		
	Challenge 1: Separation of polymer layers	Integrated solution of grinding machinery with thermal and chemical, and magnetic separation	PU/PE	Household, Leisure & Sports		Research/Pilot	IA
	Challenge 2: Delamination	Delamination with supercritical CO_2	All	All		Research/Pilot	IA
Recycling	**General (standard)**				**High**		
	Challenge: Lack of standardised polymer structures	Implement an international standard (EN or ISO)	All	All		N/A	N/A
	Chemical recycling		**3**	**All**	**Medium**		
	Challenge 1: Removal of impurities and pigments	Use of solvents	All	Packaging		Research	IA
		Chemical recycling solutions to isolate legacy additives such as solvent extraction	All	All		Research	IA
		Microwave or ultrasound chemical recycling	PET, PP, PE,	Packaging		Research/Pilot	IA
	Challenge 2: Recovery of both resin and fibre	Chemical separation processes	FRP-Epoxy, PU	All		Research	IA
	Thermochemical recycling				**High**		
	Challenge: Recycling of multi-layer films	Immersion in chemical solution for pre-treatment	PE-LD, PE-LLD, PE-HD, PE-MD	Agriculture, Packaging		Research	IA
		More solutions under section Circularity by Alternative feedstocks: 1.Plastic waste based					

IA = Innovation Action
RIA = Research Innovation Action

	Challenges	Solutions	Type of Polymer	Value chains	Impact	Short term Investment needs 2018/2020	Type of action from 2021 (Horizon Europe)
Recycling	**Mechanical recycling**				**Medium**		
	Challenge 1: Sorted waste quality	Treatment prior to mechanical recycling	PS, ABS/ SAN	All		Pilot/ Demonstration	IA
	Challenge 2: Non-reprocessable cross-linked polymers	Stable reagents	PE, PE-LD, PE-LLD, PE-HD	All		Research	RIA
	Extrusion technologies for re-processing				**Medium**		
	Challenge 1: Recyclability of FRP articles and their incorporation back into the value chain	Twin-screw extrusion and extensional flow mixers (METEOR, RMX, ...)	FRP	Automotive		Pilot/ Demonstration	IA
		Reactive extrusion process to improve adhesion between the recycled fibre and polymer matrix (compatibilisation)	FRP	Automotive		Pilot/ Demonstration	IA
		New mixers based on extensional flow (METEOR reactor)	All	All		Pilot/ Demonstration	IA
	Challenge 2: Recyclability of aged polymers	Reactive extrusion, using a twin screw extruder or a mixer	All	All		Pilot/ Demonstration	IA
	Challenge 3: Non-standardised polymer mixes	Online recycling process control to provide constant compound final properties	All	All		Pilot/ Demonstration	IA
	Post-processing		**3**	**All**			
	Challenge 1: Packaging contamination	Polyethylene boosters or additive systems	PE	Packaging		Pilot/ Demonstration	IA
	Challenge 2: Material blends phase morphology	Standardisation protocols	PE-LD, PE-HD, PP	Packaging		Research	RIA

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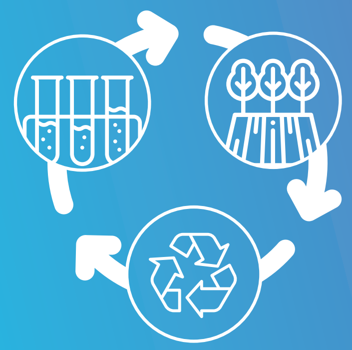
RIA = Research Innovation Action

	Challenges	Solutions	Type of Polymer	Value chains	Impact	Short term Investment needs 2018/2020	Type of action from 2021 (Horizon Europe)
Recycling	**Challenge 3: Polyolefins contamination**	Supercritical CO_2 as decontamination	PE-LD, PE-LLD, PE-HD, PE-MD	Packaging		Research/Pilot	IA
	Challenge 4: Pb restriction	Encapsulation	PVC	Building & Construction, Household, Leisure & Sports, Electrical & Electronics		Research	IA
	Challenge 5: Enhance properties of recycled materials	POF property enhancers (impact modifiers, compatibilisers and coupling agents) to enhance the properties of recyclates	All	All		Demonstration/ Industrial/first of a kind	IA
		Machine learning for processing	All	All		Research	RIA

IA = Innovation Action
RIA = Research Innovation Action

Circularity by Alternative Feedstock



This section covers innovation in plastics based on alternative sustainable feedstocks, coming from waste/residues of biomass origin, industrial gases but also plastics origin.

1. Plastic waste based

This section is also addressed above in the section on circularity by design. Here a slightly different focus is given here on the use as feedstocks into refineries or crackers to revert to monomers.

1.1. Thermal recycling

Specific Challenge:

Fibre degradation in FRP.
Limit fibre degradation (mechanical resistance, length, fibre structure) along with increasing polymer matrix recovery.

Scope:

In the specific case of composites, especially in automotive applications, fluidised bed pyrolysis can be used and further optimised (in terms of process parameters like time and temperature).

Technology Readiness Level

Activities should go from TRL 4 and achieve TRL 8 at the end of a project.

1.2. Thermo-chemical recycling

Specific Challenges:

Replace only-thermal based processes.
Thermal-based processes for molecular chain-cutting systems are highly energy intensive, and in some cases, they degrade the surface of the recycled material. Chemical processes can provide a better alternative, but issues of high cost of utilities (steam, electric power, water); low yields; and low-quality rate of the final product need to be addressed in order to make it more financially, industrially and environmentally attractive. The main outcome of the process is an oily liquid (synthetic crude oil), which can be upgraded into raw materials for chemicals and materials. The composition of the liquid varies depending on the input waste. Some purification technologies to remove hazardous chemicals exist and new ones are under development. Chemical recycling could be applied to many plastics streams which are not suitable for eco-efficient mechanical recycling.

Scope:

Chemical recovery technologies can be developed through depolymerisation process (able to handle varying input material qualities), with suitable catalysts and efficiency improvements. Solvolysis types of processes can be combined with microwave energy systems to make the process more cost effective (energy and time savings).

Specific Challenges:

Recycling of mixed post-consumer wastes (MPW) is challenged by the presence of mono- and multi-layers films that are typically difficult to separate and recycle due to incompatibility of layers, contamination with food, the presence of pigments, fillers, etc.

More generally, for all these mixed plastic wastes, chemical recycling of the target waste can be done by 1) low severity pyrolysis, 2) high severity catalysis and 3) catalytic pyrolysis. The final relative technological and economical capabilities of these three routes are not clear yet.

Furthermore, chemical recycling performance is also sensitive to contamination of the feedstock with macroscopic contamination (metal parts, minerals, etc.) and chemical contamination (chlorine, oxygen and nitrogen containing materials requires specifications on feedstock in establishing maximum permitted levels). Good selection before the process steps is required and the contamination still entering the pyrolysis process has to be handled by separation and purification. However, processes to remove contaminants of the products from pyrolysis processes are still not well-defined and can be cost intensive.

Scope:

Develop further catalytic depolymerisation polyolefins processes, develop the necessary separation and purification technologies to satisfy the purity requirements of the process feedstocks and study the influence of processing conditions on different types of feedstocks. Gasification (possibly combined with biological and chemical post-treatment) is another route for chemical recycling (syngas leading to raw materials for chemicals and materials).

In the case of polyurethane, glycolysis and acidolysis types of processes should be developed.

Technology Readiness Level

Some technologies have a high TRL for producing liquid fuels (7-8) but chemical recycling back to monomers with the required quality are at lower TRL (4-5). These are expected to reach TRL 7-8 in five years.

1.3. Biological recycling

Specific Challenges:

Depolymerisation of polymers back to monomers.

The biological recycling (controlled bio degradation) of condensation polymers (PU, PET etc.) needs to be done in a controlled way so that monomers or new molecules can be consistently recovered from such a process.

Scope:

Whole-cell bacterial catalysts (bacteria and enzyme) or pure enzyme using synthetic biology for optimisation of enzyme candidate selection.

Technology Readiness Level

Activities should go from TRL 5 and achieve TRL 8 at the end of a potential project.

2. Agricultural, forest biomass and waste based raw materials

Side streams of both agricultural and forest feedstock are a good source of feedstock for bio-based polymers.

Challenges:

Forest and agricultural residues represent an abundant and potentially sustainable source of biomass, which could be used as a feedstock for chemicals, fuels and materials in the future. The C6 sugars can be converted into chemical intermediates, and lignocellulosic biomass in general can be converted to thermoplastic materials by chemical and/or enzyme treatments. Materials in which natural fibres are combined with bio-based thermoplastic matrix, such as Sulapac, can provide sustainable bio-based solutions for certain applications, e.g. in the area of packaging. Major challenges are associated with conversion inefficiencies for this biomass-to-product approach.

Scope:

In the area of C6 sugars conversion, catalytic process can achieve higher yields and better selectivity during the conversion of sugar from agricultural sources to industrial feedstock for renewable polymer production.

Example: Cellulose can be esterified to produce thermoplastic.

Technology Readiness Level

TRL 6 to 9.

Specific Challenge:

The main challenge for biomass conversion into aromatics BTX (Benzene, Toluene, Xylene) is finding the optimal feedstock and process to maximise yield in order to get a cost-efficient process.

Scope:

Technologies like Integrated Cascading Catalytic Pyrolysis (ICCP) can be used to produce building blocks for ABS, PS, PET, and PO.

Technology Readiness Level

From TRL 5 to TRL 9 in five years.

Specific Challenge:

High-energy demand of enzymatic processes Lignin, hemicellulose, cellulose, biopolymers can be obtained in large volumes from the fractionation of second generation biomass and do not interfere with food applications. However, they exhibit high structural complexity (composite structures, higher O/C ratios, low densities) that currently result in high-energy demand for manufacturing them in biomass-to-product strategies. Major challenges are associated with conversion inefficiencies.

Scope:

Fundamental research is necessary to find highly active and selective catalysts, high-yield fermentation processes, and atom-efficient metabolic reaction pathways in order to increase the overall process efficiencies.

Technology Readiness Level

TRL 3 to 9.

Specific Challenge:

Discrepancy of mixed feedstock and specifically active enzymes

Agricultural and forest waste streams very often are mixtures of different bio-based products. In contrast most of the enzymes used are specific to certain product groups.

Scope:

A chemical approach in the use of bio-based feedstock with a given specification in traditional, established processes and assets. This mass allocation of biomaterials into a fossil-based cracker feed creates a mixture of hydrocarbons that are partly of plant origin instead of being 100% fossil. An advantage of this technology is the use of existing assets reducing necessary investment cost and manufacturing costs compared to fermentative down-stream technologies. Also, the derived products have the same performance.

Technology Readiness Level

TRL 3 to 7 in five years.

3. CO_2/CO-based

This section covers technologies to convert CO_2 (and/ or CO from gaseous industrial effluents) into polymers or chemical building blocks which can in turn be converted into polymers.

Specific Challenge: Cost competitive access to CO2

Energy efficient and cost-effective purification of gaseous industrial effluents, up-to the appropriate level of purification required for the chemical conversion process, is essential to deployment of CO_2–to-plastics technologies, in particular for commodity plastics. The optimisation of state-of-the-art technologies should be complemented by new capture and purification technologies.

Scope:

Smart design and sustainable production of advanced materials - in particular membranes- can be key for more efficient capture and purification of CO_2 containing streams, with a capacity to reduce process complexity and cost.

Specific Challenges: Convert CO2 into usable building blocks.

Several pathways exist for conversion of CO_2 into chemical building blocks for the production of various types of polymers.

Scope:

- Direct conversion of CO_2 to polycarbonate-etherols (polyol) for polyurethanes, poly (propylene) carbonate.
- Polymers from CO_2-derived olefins, from CO_2-derived vinyl monomers, from CO_2-derived olefin oxides, from CO_2-derived olefin derivatives.
- Polymers from CO_2-derived non-olefinic intermediates (e.g. PTHF or PU without isocyanate).

Technology Readiness Level

Several technologies under the above categories exist at various different levels of TRL, the lowest being the development of catalysed copolymerisation of ethylene oxide with CO_2 and the highest being the copolymerisation of CO_2 with propylene oxide which is at TRL 8.

Table 5: Circularity by Alternative Feedstock

Plastic waste based

Challenges	Solutions	Type of Polymer	Value Chains	Impact	Short term Investment needs 2018/2020	Type of action from 2021 (Horizon Europe)
Thermal recycling				**Low**		
Challenge 1: Fibre degradation in FRP	Fluidised bed pyrolysis	Epoxy-FRP	Automotive		Research/Pilot	IA
Thermochemical recycling				**High**		
Challenge 1: Replace only-thermal based processes	Chemical recovery through depolymerisation process (able to handle varying input material qualities)	PET, PU, PA, PBT	Automotive, Electrical & Electronic, Household Leisure & Sports		Research	IA
	Combine solvolysis with a microwave energy system	PET, PUR, PS, PS-E, FRP	Packaging, Building & Construction, Automotive		Research	IA
Challenge 2: Recycling of multi-layer films	Catalytic depolymerisation process for degradation of polyolefins	PE-LD, PE-LLD, PE-HD, PE-MD	Packaging		Research	RIA
Challenge 3: Re-cycling of mixed plastic waste (MPW)	Next generation pyrolysis process	PE, PP, PS	All		Research	IA
	Gasification (possibly combined with biological and chemical post-treatment)	All	All		Pilot/ Demonstration	IA
Challenge 4: Depolymerisation of condensation polymers	Glycolysis	PU	Automotive, Household, Leisure & Sports		Research/Pilot	IA
Biological recycling				**Low**		
Challenge 1: Depolymerisation of polymers back to monomers	Whole-cell bacterial catalysts	PET/PU	Packaging, Automotive, Household, Leisure & Sports		Research/Pilot	IA
	(Pure) enzyme recycling	PET/PU	Packaging, Automotive, Household, Leisure & Sports		Research/Pilot	IA

IA = Innovation Action
RIA = Research Innovation Action

Agricultural forest biomass and waste based raw materials

Challenges	Solutions	Type of Polymer	Value Chains	Impact	Short term Investment needs 2018/2020	Type of action from 2021 (Horizon Europe)
Conversion of biomass				**Medium**		
Challenge 1: Convert C6 sugars into chemical intermediates	Catalytic process	Bio-based	All		Pilot/ Demonstration	IA
Challenge 2: Transformation of forest biomass and residues	Esterification of cellulose	Bio-based	All		Pilot/ Demonstration	IA
	High yield fermentation with efficent metabollic patways				Pilot/ Demonstration	IA
Biomass into conventional processes						
Challenge 1: Conversion from biomass into competitive BTX for building blocks production	Integrated Cascading Catalytic Pyrolysis (ICCP)	Bio-based	All		Pilot/ Demonstration	IA
Challenge 2: Discrepancy of mixed feedstocks and specifically active enzymes	Bio-based feedstock introduced in traditional processes	Partially bio-based	All		Research/Pilot	IA

IA = Innovation Action
RIA = Research Innovation Action

CO_2/CO based

Challenges	Solutions	Type of Polymer	Value Chains	Impact	Short term Investment needs 2018/2020	Type of action from 2021 (Horizon Europe)
Cost competitive access to CO_2				**Medium**		
Challenge: Capture CO_2 to use as feedstock	Polymeric membrane for CO_2 storage, separation and release	N/A	N/A		Research/Pilot	IA
CO_2 conversion				**Medium**		
Challenge: Convert CO_2 into usable building blocks	New chemical monomers to obtain PU (polyurethane) from CO_2	PU	Automotive, Household, Leisure & Sports		Research	RIA
	Paraformaldehyde as building block for polyols	PU	Automotive, Household, Leisure & Sports		Research	IA
	Catalysed copolymerization of propylene oxide and CO_2	PU	Automotive, Household, Leisure & Sports		Demonstration/ Industrial/first of a kind	IA
	Catalysed copolymerization of ethylene oxide and CO_2	PU	Automotive, Household, Leisure & Sports		Research	RIA
	Transformation of industrial waste gases (mixed CO/CO_2 steams) into intermediates for polyurethane plastics for rigid foams/building insulation and coatings.	PU	Building & construction		Research	IA
	Production of oxalic acid by chemically reducing CO_2		Packaging, Household, Leisure & Sports		Research	IA
	Production of other C2-acids (electro) catalytic		Packaging, Household, Leisure & Sports		Research	IA

IA = Innovation Action
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Glossary

ABS-HIPS	Acrylonitrile-butadiene-styrene – High Impact polystyrene
ABS-SAN	Acrylonitrile-butadiene-styrene – Styrene acrylonitrile
AI	Artificial intelligence
BrFR	Brominated flame retardants
BTX	Benzene, Toluene Xylene
CLT	Cross-linked thermosets
CO2	Carbon dioxide
CVD	Chemical vapour deposition
DCPD	Polydicyclopentadiene
DEHP	Di-2-ethylhexyl phthalate
EFSA	European Food Standards Agency
EPS	Expanded polystyrene
FDA (US)	Food and Drug Administration
FRP	Fibre reinforced polymer
HBCD	Hexabromocyclododecane
ICCP	Integrated Cascading Catalytic Pyrolysis
LCA	Life Cycle Assessment
LCC	Life Cycle Costs
LIBS	Laser-Induced Breakdown Spectroscopy
MIR-T	Mid Infrared Thermography
MPW	Mixed post-consumer waste
NIR	Near infrared
PA	Polyamide (aka Nylon)
PA6/PA66	Nylon 6 / Nylon 66
Pb	Lead
PBS/PBSA	Polybutylene Succinate / Polybutylene Succinate Adipate
PBT	Polybutylene terephthalate (also PTMT)
PC	Polycarbonate
PE	Polyethyene
PE-HD	Polyethyene - high density
PE-LD	Polyethyene – low density
PE-LLD	Polyethyene - linear low density
PE-MD	Polyethyene - medium density
	Glossary
PEC	Polyester carbonate
PEF	Polyethylene Furanoate
PET	Polyethylene terephthalate
PHA/PHB	Polyhydroxyalkanoates / Polyhydroxybutyrate
PLA	Polylactic acid
PMMA	Polymethyl methacrylate
PO	Polyolefin
POM	Polyoxymethylene
PP	Polypropylene
PPC	Polypropylene carbonate
PS	Polystyrene
PT	Polythiophene
PTFE	Polytetrafluoroethylene
PTHF	Polytetrahydrofuran
PU/PUR	Polyurethane
PVC	Polyvinyl chloride
PVD	Physical vapour deposition
SIRA	Strategic Innovation and Research Agenda
TBS	Tracer based sorting
TPS	Toughened polystyrene
TRL	Technology readiness level
TS FRP	Thermoset Fibre reinforced polymer
UV	Ultraviolet
VIS	Visible
WEEE	Waste from electrical and electronic equipment
XRF	X-ray fluorescence
XRT	X-ray transmission

About the partners

SusChem is the European Technology Platform for Sustainable Chemistry. It is a forum that brings together industry, academia, policy makers and the wider society. SusChem was officially launched in 2004 as a European Commission supported initiative to revitalise and inspire European chemistry and industrial biotechnology research, development and innovation in a sustainable way.
www.suschem.org

The European Chemical Industry Council - Cefic is a committed partner to EU policymakers, facilitating dialogue with industry and sharing broad-based expertise. Cefic represents large, medium and small chemical companies across Europe, which directly provide 1.2 million jobs and account for 14.7% of world chemical production. Based in Brussels since its founding in 1972, Cefic interacts on behalf of its members with international and EU institutions, non-governmental organisations, the international media, and other stakeholders.
www.cefic.org

PlasticsEurope is a leading European trade association with centres in Brussels, Frankfurt, London, Madrid, Milan and Paris. The association networks with European and national plastics associations and has more than 100 member companies that produce over 90% of all polymers across the EU28 member states plus Norway, Switzerland and Turkey.
www.plasticseurope.org

European Plastics Converters (EuPC) is the EU-level trade association, based in Brussels, representing more than 50 000 companies in Europe, which produce over 50 million tonnes of plastic products every year. Plastics converters (sometimes called «Processors») are the heart of the plastics industry. They manufacture plastics semi-finished and finished products for an extremely wide range of industrial and consumer markets - the automotive electrical and electronic, packaging, construction and healthcare industries, to name but a few.
www.plasticsconverters.eu

The European Composites, Plastics and Polymer Processing Platform (ECP4) is an industry-driven collaboration that unites 25 members from 13 countries amongst the top-level European research institutions, regional plastic clusters, and EU-level industrial organisations of plastics and composites converters. ECP4 brings innovation partners together to identify opportunities for collaborative research.
www.ecp4.eu

About SusChem

SusChem is the European Technology Platform for Sustainable Chemistry. It is a forum that brings together industry, academia, policy makers and the wider society.

SusChem's **vision** is for a competitive and innovative Europe where sustainable chemistry and biotechnology together provide solutions for future generations.

SusChem's **mission** is to initiate and inspire European chemical and biochemical innovation to respond effectively to societal's challenges by providing sustainable solutions.

At SusChem we believe that sustainable chemistry can inspire a change of pace and the new mind-set that society needs in order to become (more) sustainable, smart and inclusive. In partnership with European and national public authorities, SusChem contributes to initiatives that aim to provide sustainable solutions to society's big challenges. Together we develop and lead large-scale, integrated research and innovation programmes with chemical sciences at their core. These public private initiatives link research and partners along the value chain to real world markets through accelerated innovations.

SusChem across Europe

SusChem has established a network of National Technology Platforms (NTPs) in 17 countries across Europe: Austria, Belgium, Bulgaria, Czech Republic, France, Germany, Greece, Italy, Netherlands, Poland, Romania, Slovenia, Spain, Switzerland, Sweden, Finland, and United Kingdom.

NTPs help to connect SusChem thinking with national and regional programmes. It also facilitates transnational collaboration and advice SusChem at the European level on collective national priorities that need to be considered in European initiatives.

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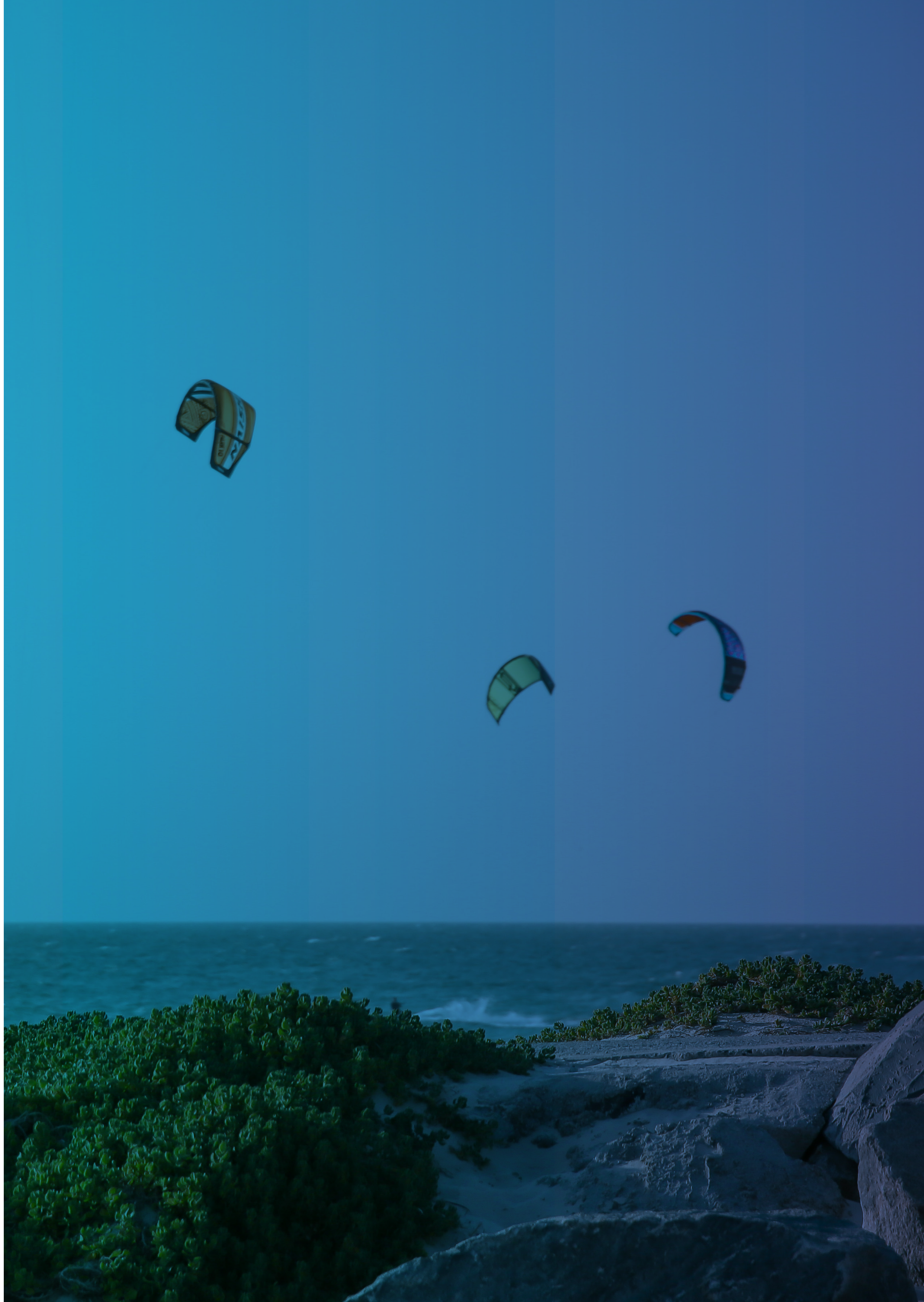

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