European Commission

A CIRCULAR ECONOMY FOR PLASTICS

Insights from research and innovation to inform policy and funding decisions

Research and Innovation

A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions

European Commission
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EUROPEAN COMMISSION

A CIRCULAR ECONOMY FOR PLASTICS

Insights from research and innovation to inform policy and funding decisions

Edited by Michiel De Smet and Mats Linder

2019 Directorate-General for Research and Innovation

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INTRODUCTION

The challenges and opportunities posed by the current plastics system demand fundamental change in which research and innovation (R&I), enabled and reinforced by policymaking, play a crucial role. While plastics bring benefits as a functional material, the current system has significant unintended drawbacks, including economic loss of material value and environmental damage, such as marine litter. It has become evident that the plastics economy needs to change from a system that produces waste by design to one that preserves the value and benefits of plastics, but eliminates these drawbacks. While this transition can be accelerated by the accumulated effect of multiple small steps, such incremental progress will not suffice – systemic change powered by R&I and enabled through policymaking is the only long-term solution.

Europe is taking responsibility to deal with this global problem through a range of measures, while capturing the opportunities created by moving towards a circular economy for plastics. These actions are mostly being taken under the umbrella of the Circular Economy Package, and they have resulted in, *inter alia*, a comprehensive waste legislation review, the publication of the first-ever Europe-wide strategy on plastics, and a communication on options to address the interface between chemical, product and waste legislation. As outlined in *A European Strategy for Plastics in a Circular Economy*, Europeans can turn the plastics challenges into opportunities and set an example for resolute action at a regional, national, European and global level. In addition to this vision, this EU Plastics Strategy provides a list of measures that aim to improve the economics and quality of plastics recycling, to curb plastic waste and littering, to drive innovation and investment towards circular solutions, and to harness global action. The strategy also recognises innovation as a key enabler for the transformation of the system, with innovation areas spanning the entire value chain: renewable energy and feedstock, product design, business models and reverse logistics, collection and sorting mechanisms, mechanical and chemical recycling technologies, compostability and biodegradability. In addition, innovation is relevant for identifying and assessing the impact of hazardous chemicals and plastic pollution, as well as developing safer alternatives and remediation technologies.

This report adds to the Commission's efforts towards a circular economy for plastics by strengthening the science-policy interface based on scientific evidence. By providing recommendations for sectoral policymaking and insights for strategic programming from a research and innovation perspective, it aims to inform policymakers, ranging from EU institutions to local authorities, researchers, innovators and other interested stakeholders. This report's insights have been produced by extending a DG Research & Innovation 'Projects for Policy' approach, capturing insights from EU-funded R&I projects, the research community and a wider stakeholder group. More information on the process can be found in APPENDIX: The report writing process. In line with the Innovation Principle, this report's recommendations aim to be outcomes-oriented and future-proof, and they aspire to benefit citizens, business and the environment. The potential solution space covers innovative business models, products and materials, including but also going beyond plastics.

In line with the Commission's objectives, the insights gathered in this report aim to support the transition towards a circular economy for plastics. In the long term, as explained in the EU Plastics Strategy, such a circular system would envision plastics to be produced with renewable energy and feedstock, and plastic products designed to be used, reused, repaired and (mechanically, chemically or organically) recycled, such that this material can flow through society with full transparency and high-value use without posing risks to human health and the environment. This system should harness the benefits of plastics, while achieving better environmental, economic and social outcomes from a life-cycle perspective. In this way, the transition will contribute to the objectives laid out in the EU Plastics Strategy and other domains, including resource efficiency, climate change, bio-economy and the UN Sustainable Development Goals. In APPENDIX: Link to EU Plastics Strategy, a comparison is given between policy recommendations identified in this report and the measures of the EU Plastics Strategy (Annex I), in order to understand coherence. Several of the policy recommendations have already been, or are being, dealt with following related initiatives, including the EU Plastics Strategy and the Bioeconomy strategy, updated in 2018.

Taking a research and innovation perspective, this report does not aim to cover all aspects of the plastics system. Given the complexity and breadth of the plastics landscape, some elements are not dealt with. For example, different types of plastics and their applications, and the contribution to economic growth and jobs are not covered in detail, although a summary is provided in APPENDIX: Overview plastics and its applications. These aspects could bring additional angles and insights to the conclusions of the report. While it does not claim to be exhaustive, this report does provide a comprehensive overview of the plastics system and related gaps in research and innovation, and of the preconditions to achieve better economic, environmental and social outcomes.

EXECUTIVE SUMMARY

State of play

In just a few decades, plastics have radically changed our economy and society. Combining excellent functional properties with low cost, these materials are omnipresent and their global production volume is expected to continue to grow far beyond the 2016 figure of 335 million tonnes. However, the current plastics system poses significant economic challenges, with an estimated annual material value loss of EUR 70-105 billion globally, as well as environmental ones, including the estimated annual release of 75 000 to 300 000 tonnes of microplastics into EU habitats. These shortcomings demand systemic change in which R&I, enabled and reinforced by policymaking, plays a crucial role.

The unintended impacts of plastics on society and the environment

A crucial challenge of the linear plastics economy is the omnipresent and persistent plastic pollution, resulting in economic and environmental costs to society. While public decision-making on plastic pollution is moving forward, the scientific understanding of this issue is still fragmented, especially regarding its sources and impacts. Improving this understanding is vital in order for policies to address the causes and effects of plastic pollution. However, the complex nature of this issue means that developing and implementing effective solutions must be done without complete knowledge about the root causes.

Another shortcoming of the current plastics economy is the leakage of, and potential exposure to, substances of concern to human and environmental health. Researchers employ different methods to evaluate the hazards and risks of chemicals used intentionally, or present non-intentionally, in plastics, and policymakers aim to mitigate these risks through a range of legislation. However, differences in which categories of substances should be assessed for the various applications, and at what stage in the supply chain, has led to an incomplete and potentially contradictory regulatory situation limiting the effectiveness of such initiatives.

Novel sources, designs and business models for plastics in a circular economy

In the past, most R&I in plastics has focused on developing novel sources of feedstock and specialised materials. The large-scale capital-intensity and decades-long optimisation of the petrochemical industry have made and still make it difficult to scale up the production of new materials that do not fit into the existing infrastructure. Bio-based feedstock, which has the potential to constitute a renewable chemicals platform for plastics and additives, can tap into this infrastructure in selected cases. However, to realise the full potential, new dynamic, small-scale, decentralised business and biorefinery models will also be required. In addition, more cross-value-chain collaboration and systems thinking are needed to valorise the variety of biological feedstock across Europe.

While this material innovation is crucial, a circular economy framework also requires fundamentally new approaches to the underlying business model and product designs. Concepts such as ecodesign and product-service systems challenge the current linear production and consumption paradigm through elimination or reuse, in line with the waste hierarchy. However, despite emerging evidence of such ideas also being tested in the plastics value chain, most design innovation has not yet taken the systemic approach required to turn these concepts into viable businesses. This situation is, for example, reflected in many R&I projects being focused on introducing a new material without designing for a circular pathway in the underlying system.

To keep products and materials in use safely, the plastics system needs more information transparency. Unravelling part of the plastics landscape complexity, this transparency should connect upstream design and production with the use phase and after-use collection, sorting and recycling. Technological developments and societal trends suggest the ability to create more of this transparency, but such systems are mostly being explored only at the research level.

Circular after-use pathways for plastics

Collecting, sorting and recycling plastics brings economic and environmental benefits, but the current systems face capacity and modernisation challenges across Europe. There is significant untapped potential in processing used plastics, in terms of increasing volumes, quality and yield of reprocessed plastics. Improvements are partly driven by technical innovations, including automated and robotics-powered collection and sorting, and novel chemical recycling methods to obtain virgin-grade plastics. Harmonisation of collection systems, while allowing adaptation to local conditions, is another important driver in retaining value.

There are still many unanswered questions about how to set up a robust after-use system that is adapted to the increasingly complex plastics landscape. Complementary to mechanical recycling, chemical recycling of plastics could play an important role by expanding the ability to treat complex material streams and providing virgin-quality recycled materials. In addition, the use of compostable material in selected applications could enable organic recycling of bio-waste. However, the different recycling options all face challenges in dealing with economic viability, technical performance, legal status, environmental concerns and supporting infrastructure. What these after-use solutions also have in common is that their performance and the extent of value creation are subject to the design and material choice of each plastic object on the market – an insight that reinforces the importance of design and innovation upstream. Hence, a strategic vision is needed on how to integrate this set of different after-use pathways into the general plastics system, in order to maximise material value retention and provide direction for future innovation.

Challenges and knowledge gaps

So far, innovations have often focused on improving a single issue, rather than taking the entire plastics system into account. Past R&I efforts in the plastics landscape have often focused on a specific subdomain, such as a certain packaging barrier property or conversion of a particular biomass type. As R&I requires collaboration between a broader range of stakeholders and capabilities, applying a systemic, interdisciplinary approach that covers the entire plastics supply chain is challenging. However, without such an approach, R&I projects leave significant questions unanswered about how the innovation depends on other steps in the value chain, how it affects the wider system and how to practically implement the findings. This challenge has been identified before, and there are indications that systems thinking is being increasingly applied in R&I projects, for example, through embedding cross-value-chain collaboration. Nevertheless, these actions are only a fraction of what will be needed for systemic change, especially in the case of plastics.

An increasingly complex plastics landscape creates additional challenges for effective tracking, collection, sorting and recycling of used plastics. New complex materials and products allow differentiation and provide improved properties for the benefit of users, including food preservation, citizens' convenience and lightweight items. However, the increasing complexity of plastics, sometimes combined with other materials, makes it more difficult for the collection, sorting and recycling sectors to adapt and to innovate towards technologies that improve the quality of recycled materials. In addition, it makes it harder for the end user, i.e. the citizen, to understand and interact with the plastics system, affecting collection rates and sorting yields. Finally, new complex materials make it more difficult to know what substances are on the market and to assess whether there are risks for human and environmental health.

Limited innovation has happened in business model design, which is critical to prevent plastics from becoming waste. According to the available reporting, many of the reviewed R&I projects focus on material and technology performance, while not really challenging the underlying business model, such as the single-use nature of applications. As a result, limited efforts go into novel designs fit for a circular economy. For example, product design and business model innovations that prevent plastics from becoming waste, such as reuse enabled through digital technologies, would directly address one of the root causes of plastic pollution. Yet, examples of such bottom-up innovations are limited.

Most investors have limited experience with the development of high-risk, disruptive innovations towards a circular economy for plastics. The inherent uncertainty of investing in innovation especially holds in the plastics system due to its complexity and the need for innovations that seek to fundamentally change the way that needs are addressed in society. Such innovations typically come with risks that are higher than and different from those in incremental improvements – not least the risks posed by ‘unknown unknowns’. While specific initiatives have been launched to overcome these difficulties, such as the European financing instrument InnovFin, most investors have little experience with this new type and amount of risk, partly reflected in the lack of oversight and assessment tools. In addition, scaling systemic innovations towards a circular economy for plastics requires several actors across the supply chain to work in a concerted way, which makes it even harder from an investor point of view. Furthermore, investment approaches would need to be able to deal with the potentially different sources of value creation and time horizons associated with circular business models, such as cash flow evolution and ownership, which are often not reflected in current practices.

Current laws and regulations are insufficient to enable cross-value-chain collaboration. To enable the multi-stakeholder collaboration needed for systemic innovations, clarity is needed on how value can be created and shared between actors in a circular economy. In addition, to incorporate the systemic angle and anticipate scale-up of innovations, collaboration should involve all stakeholders in a transparent way. While some existing measures support information exchange, policy innovations are needed to remove regulatory and legal barriers to system-wide collaboration. For example, there are challenges in creating, sharing and accounting for valuable or sensitive data across the value chain, such as information on material content and intellectual property.

There are still many knowledge gaps in the impacts of plastics on society, as there are many technological barriers for potential solutions. As for R&I in general, knowledge on the topic should strengthen the development of long-term solutions. Also, business models and technological breakthroughs are needed to implement these solutions. A detailed list of topics can be found in each chapter, including examples of knowledge gaps such as risks posed by chemicals found in plastics and the impact of microplastics on human health, and examples of innovation challenges, including improved automated sorting and depolymerisation on an industrial scale. Of course, due to the complex nature of this issue, lack of knowledge and technological hurdles should not prevent the development and implementation of solutions.

Policy recommendations and R&I priorities

Policy recommendations and R&I priorities have been identified based on the state of play and on challenges and knowledge gaps. The former can be found on the next page and in APPENDIX: Overview policy recommendations and the latter in APPENDIX: Overview R&I priorities.

SHORTLIST OF POLICY RECOMMENDATIONS

The list below represents a high-level synthesis of recommendations proposed by the experts and edited following feedback from a wider stakeholder group. More details and the underlying reasoning can be found in the different chapters and in APPENDIX: Overview policy recommendations.

General insights across the plastics value chains

1. Facilitate collaboration across the plastics value chains towards a common vision to trigger actions on a regional, national, European and global level.

2. Develop, harmonise and enforce regulatory and legal frameworks guided by systems thinking to connect the different actors of the plastics value chain(s).

3. Set up, connect and fund mechanisms to coordinate strategically the transition towards a circular economy and to invest in upstream and downstream capacity across Europe.

4. Provide funding for research and a range of financial incentives for systemic innovation in business models, products and materials fit for a circular economy for plastics.

5. Educate and support citizens, companies and investors on the transition towards a circular economy for plastics.

Part I: The unintended impacts of plastics on society and the environment

6. Harmonise definitions, frameworks for data gathering and analyses of plastic pollution sources, pathways, fates and impacts at a European and global level.

7. Develop open collaboration platforms to enable more comprehensive analyses and frequent benchmarking on plastic flows and impacts, to provide information on and for investments, and to inform industry, government and the public.

8. Enforce, harmonise and adapt existing EU chemical regulations (e.g. REACH, Toy Safety Directive, regulation on food contact materials) based on a systems thinking approach.

9. Develop regulatory frameworks with additional requirements for additives and other chemicals in plastic products based on the overall migrate and the potential toxicity of the mixture from combined exposure to finished articles.

10. Provide business support to identify and reduce chemical hazards, and to create transparency on the socio-economic and environmental impacts of plastics and on successful alternative solutions.

Part II: Novel sources, designs and business models for plastics in a circular economy

11. Facilitate gathering, sharing and trading of reliable information and data on business models, technologies and material composition to foster open innovation and activation of industry, government, innovators and the public.

12. Set up a coordination mechanism, combining technical, commercial and behavioural expertise, for tracking material flows and renewable feedstock inventories, and for strategic long-term investments in plastics production, collection, sorting and recycling infrastructure across Europe.

13. Develop regulatory measures such as standards, assessment methodologies, ecodesign requirements and incentives such as Extended Producer Responsibility (EPR) schemes with modulated fees, to evaluate and steer design of business models and products towards

elimination of challenging items, use of renewable or recycled feedstock, reuse and cost-effective recycling, and to fund innovation in this field (e.g. through Packaging and Packaging Waste Directive (PPWD), Ecodesign Directive, Waste Framework Directive (WFD)).

14. Set up, connect and participate as an active stakeholder or shareholder in investment instruments to enable investors and lenders to provide funds for circular economy business models (Horizon Europe).

15. Provide regulatory, legal and financial incentives to support long-term R&I in chemicals and materials based on renewable feedstock and recycled materials, and their scale-up towards a self-sustaining critical mass, while ensuring environmental benefits benefits based on a holistic impact assessment across the life cycle.

16. Provide information for citizens and businesses about materials based on renewable feedstock and about recycled materials by developing standards, labels and a holistic impact assessment framework.

17. Incorporate systems thinking and circular design in the education curriculum at all levels.

Part III: Circular after-use pathways for plastics

18. Develop a holistic vision for an after-use plastics system in Europe, incorporating reuse and repair, and mechanical, chemical and organic recycling, and develop a methodology for comparing these different options based on feasibility, and on the environmental, economic and social impact.

19. Facilitate gathering and sharing of reliable information and data on virgin and recycled material composition and on collection, sorting and recycling performance and best-practice cases, to enable cross-value-chain collaboration and compatibility.

20. Develop a regulatory framework to harmonise collection systems, allowing a certain degree of local adaptation to socio-economic conditions.

21. Develop regulatory measures, such as ecodesign requirements, and financial incentives, such as EPR with modulated fees, integrating new digital technologies, to evaluate and steer design of business models and products towards elimination of challenging items, use of renewable or recycled feedstock, reuse and cost-effective recycling, and to fund innovation in this field (e.g. through PPWD, Ecodesign Directive and WFD).

22. Develop and implement harmonised standards for the quality of mechanically and chemically recycled plastics, and for verification of recycled content, taking into account safety and application areas.

23. Provide regulatory and fiscal incentives to stimulate the demand for recycled plastics, such as public procurement, and to take into account the costs of negative externalities associated with different feedstock types, such as reduced value added tax (VAT).

24. Review and update waste legislation to incorporate the latest recycling technologies, including end-of-waste criteria for plastics, guided by systems thinking and the European strategy for plastics in a circular economy.

25. Harmonise regulatory efforts, including standardisation, to provide direction for R&I and implementation of compostable and biodegradable materials, and to establish clear communication and guidance for citizens and business.

PART I:

THE UNINTENDED IMPACTS OF PLASTICS ON SOCIETY AND THE ENVIRONMENT

Without a doubt, plastics bring multiple benefits to society. Yet, there are growing concerns and mounting evidence that plastics also considerably affect environmental and human health, and that the negative impacts are accumulating. The first part of this report reviews these unintended effects, and it shows how R&I helps to better understand and address them.

1 PLASTIC POLLUTION

With a global production of 335 million metric tonnes in 2016, plastics have become the most abundant anthropogenic materials besides steel and concrete (PlasticsEurope, 2018). Since the beginning of its mass production in the 1950s, humankind has produced about 8 300 million tonnes of plastics. Despite the immense societal benefits, it is estimated that about 5 800 million tonnes of plastics, representing 70 % of the total amount, have become waste, of which 84 % or 4 900 million tonnes has been disposed of in landfills or in the environment (Geyer, Jambeck & Law, 2017).

The persistence and mobility of plastics bring several benefits, but it also entails that plastic litter is now ubiquitously distributed across the globe. The pervasiveness of plastic pollution as well as the potential negative effects on ecosystems and human health have triggered public concerns in the European Union and elsewhere. According to Eurobarometer, the majority of Europeans are worried about the environmental (84 %) and health impacts (74 %) of plastics (European Commission, 2017b)[1]. These public concerns have created political momentum for addressing the issue of plastic pollution (European Commission, 2018o; European Parliament, 2018 and Council of the European Union, 2018). Some Member States have implemented legislation banning single-use lightweight carrier bags or microplastics in cosmetics. Acknowledging the systemic nature of the problem, the European Commission has reacted with a more comprehensive approach, namely *A European Strategy for Plastics in a Circular Economy* (European Commission, 2018j).

While public decision-making is moving forward rapidly, the scientific understanding of plastic pollution is still fragmentary, especially with regard to its sources, pathways and impacts. This is partly due to research into the issue being rather recent, and also because plastic pollution represents a complex challenge, in that it is an Anthropocene problem which is highly interdependent, interconnected and difficult to structure (Kramm, Volker & Wagner, 2018). Accordingly, promoting interdisciplinary research and collaboration, combining insights from environmental, engineering, and behavioural sciences and from policymaking, will significantly advance the ability to solve the problem effectively.

1.1 Sources, fate and scale of plastic pollution

The first evidence of the presence of plastic debris in the oceans emerged in the 1970s, but it took until the early 2000s for research to address the issue in a broader sense (Carpenter & Smith, 1972). In 2004, a seminal publication reported the widespread abundance of microscopic plastic particles, called ‘microplastics’, in beach and plankton samples from the United Kingdom (see Box 1) (Thompson et al., 2004). Since then, research has mainly focused on the abundance of macro- and microplastics in marine ecosystems, especially surface waters and beach sediments, and established that these are omnipresent. In comparison, less information is available on plastics in freshwater and terrestrial environments. Likewise, knowledge of the negative impacts of macroplastics on marine wildlife (e.g. through entanglement) is more abundant than of the effects of microplastics, especially regarding freshwater and terrestrial biota. For instance, less than 4 % of publications on microplastics contain the term ‘freshwater’ (Lambert & Wagner, 2018). Importantly, the pres-

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[1] *More precisely, 84 % of the respondents agreed with the statement “You are worried about the impact on the environment of everyday products made of plastics”, and 74 % agreed with “You are worried about the impact on your health of everyday products made of plastics”.*

Box 1: Definitions of environmental plastics

There is no generally accepted definition and classification framework for plastic debris. The term ‘plastic’ covers all synthetic polymers that are shaped by flow and includes the major commodity plastics PE, PP, PS, PET, PVC and PUR (ISO, 2013). On this basis, the Dutch National Institute for Public Health and the Environment (Rijksinstituut voor Volksgezondheid en Milieu or RIVM) further proposed that environmental plastics are solid, insoluble and non-degradable (Verschoor, 2015). While questions on some special cases (e.g. copolymers, composites and paints) remain, the following is an operational and pragmatic definition: ‘Environmental plastics are materials containing synthetic polymers as an essential ingredient that are found in natural environments without fulfilling an intended function.’

Environmental plastics can then be further classified according to origin, shape (beads, pellets, fragments, films, fibres), colour and size. The latter descriptor is used to differentiate between nanoplastics (< 1 µm), microplastics (< 5 mm), mesoplastics (< 2.5 cm), macroplastics (< 1 m), and megaplastics (> 1 m) (GESAMP, 2016). Note that there is no consistency in the classification as other institutions and authors use different size classes.

ence and impacts of nanoplastics have rarely been investigated, and thus are covered in this report only when data is available. More generally, as SAPEA (Science Advice for Policy by European Academies) points out in a recent Evidence Review Report, the number of papers on microplastics and nanoplastics is growing exponentially, but knowledge is not growing at the same rate (SAPEA, 2019). In this regard, SAPEA also stresses that transparent communication about uncertainties in the scientific evidence is a better approach than assuming a lack of risk.

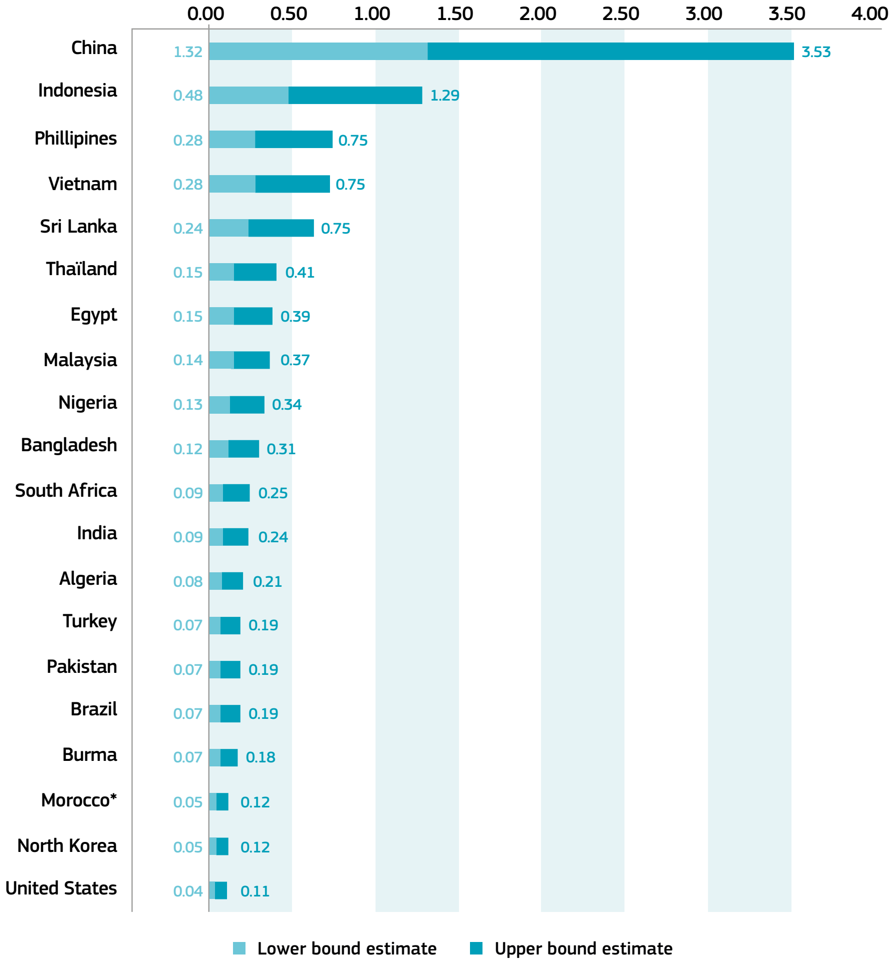
State of play

Current knowledge of the sources of plastic pollution is largely based on estimates and the definition of sources, as opposed to transport pathways, and it depends on the subsystem considered. For instance, when considering the oceans as a whole, there is consensus that the main sources of plastic pollution are land-based. Here, mismanaged waste contributes 4.8 to 12.7 million tonnes per year to the plastic inputs into the oceans (Jambeck et al., 2015). Countries with a high population density and ineffective waste management infrastructures contribute most to the oceanic plastic pollution. Collectively, the 23 coastal countries of the European Union rank 18th in the top polluters (see Figure 1).

Rivers are a major pathway for transporting plastic debris to the oceans. A recent modelling study based on mismanaged plastic waste has shown that rivers transport between 0.41 and 4 million tonnes of plastics per year to the oceans, with ten rivers in Asia and Africa transporting 88-95 % of that load (Schmidt, Krauth & Wagner, 2017), see also Figure 2. Another model based on waste management, population density and hydrological information estimated that the top 20 polluting rivers, mostly located in Asia, account for 67 % of the global total of plastic inputs into oceans (Lebreton et al., 2017). The contribution of sea-based activities, such as fisheries, lost fishing gear, waste dumping and accidental spills, is less known with few estimates available (European Commission, 2018b and Law, 2017).

Analysing which items are most commonly found on beaches is another approach to describing the sources of plastic pollution. The Ocean Conservancy collected over 13.8 million beach lit-

Figure 1: Waste estimates for 2010 for the top 20 countries ranked by mass of mismanaged plastic waste (millions of tons per year, lower and upper bound estimates)



** if considered collectively, coastal European Union countries (23 total) would rank 18th on the list.*

Source: Jambeck et al., 2015

ter items, weighing 8 346 tonnes, with their 2016 International Coastal Cleanup initiative (Ocean Conservancy, 2017). Nine of the top ten items based on item counts – cigarette butts[2], plastic bottles, bottle caps, food wrappers, grocery bags, lids, straws and stirrers, glass bottles, other bags and takeaway containers – were single-use products made of plastics. Looking at beach litter in Europe's regional seas reveals a similar situation. Across all four seas, 355 000 items were collected at 276 beaches during one campaign. The top ten items based on frequency (items per 100 m) are cigarette butts, large plastic pieces, caps/lids, drink bottles, cutlery/trays/straws, crisp/sweets packets and lolly sticks, small plastic pieces, string/cord, cotton bud sticks and drink cans (Joint Research Centre, European Commission, 2016). A prioritisation based on these findings has led to a recent proposal to ban single-use plastic items in the European Union (European Commission, 2018o). It is important to note, however, that beach litter is not necessarily representative of litter in other ocean compartments, including the sea surface, water columns and seafloor.

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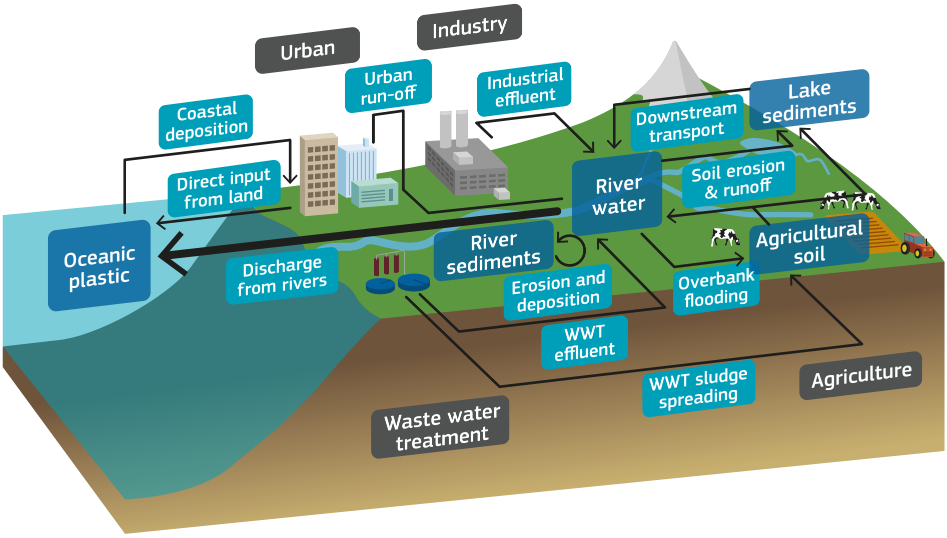
[2] *There is some debate on whether to classify cigarette butts as plastics. As they mainly consist of cellulose acetate, they are considered to be plastics here (ISO 472).*

Rather than focusing on the receiving ecosystem, the sources of plastic pollution can also be viewed from a life-cycle perspective (Eriksen, Thiel, Prindiville & Kiessling, 2018). During the production phase (including transport), plastics, especially pellets, can be lost due to mismanagement and accidents. Several case studies, for instance at the Danube River and the Swedish coast, demonstrate that plastic emissions due to spills from production can be significant (Lechner et al., 2014 and Karlsson et al., 2018). During the use phase, plastic materials and products can be released into the environment by accidental loss (e.g. during transport) and intentional uses, with microplastics in wash-off cosmetics and air blasting being the most prominent. Littering due to incorrect disposal or inefficient collection is another source, for example, taking place around bring banks (Wagner & Broaddus, 2016). In addition, abrasion and degradation during use can produce smaller plastic fragments. Here, the release of tyre and road wear particles and synthetic fibres from clothing are relevant examples[3] (Wagner et al., 2018 and Salvador Cesa, Turra & Baruque-Ramos, 2017). Using Norway as a case study, the consulting company Mepex estimated that 55.6 % of microplastics inputs into the marine environment originate from tyre wear, 12.5 % from household wear and tear (laundry dust) and 8.7 % from abrasion from ship paints and marinas (MEPEX, 2014). Most focus has been placed on the after-use phase in which plas-

Figure 2: **Overview of possible pathways for transporting plastic debris**


Urban
Industry
Coastal deposition
Urban run-off
Industrial effluent
Downstream transport
Lake sediments
Direct input from land
River water
Soil erosion & runoff
Oceanic plastic
River sediments
Agricultural soil
Discharge from rivers
Erosion and deposition
Overbank flooding
WWT effluent
WWT sludge spreading
Agriculture
Waste water treatment

Source: Horton et al., 2018

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[3] *As tyre dust particles are typically made of natural and/or synthetic rubber, some exclude these from the category 'microplastics'. Many research studies on microplastics include them in the scope, as is the case here.*

tics become waste that is emitted into the environment by littering and mismanagement.

Understanding the fate of plastic pollution is important for predicting sources and accumulation zones as well as its impact. The fate of plastics released into the environment involves two processes, namely plastics transport and their degradation. The transport mechanisms vary between environmental compartments. Research has focused mainly on the transport in aquatic systems, which depends on the physical properties of the plastics (e.g. density determining buoyancy) as well as the morphology and hydrodynamics of the system (Blasing & Amelung, 2018). It is important to understand these processes to predict hotspots of plastic pollution and identify affected habitats accordingly. One well-researched case is the accumulation of buoyant litter in the oceanic gyres (Eriksen et al., 2013 and Lebreton et al., 2018).

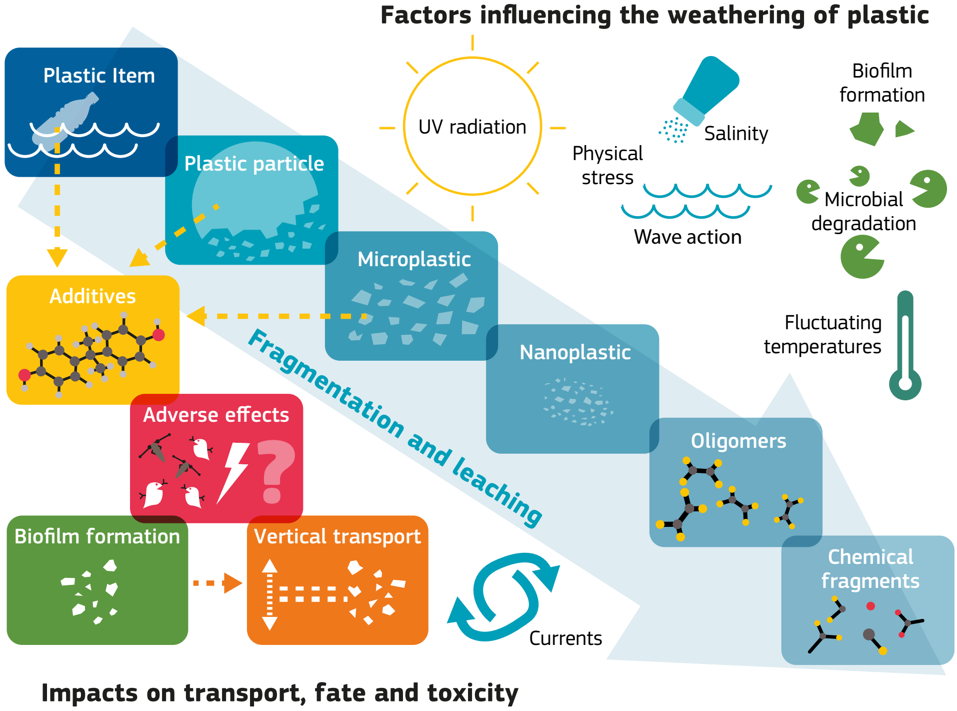
It is estimated that most environmental plastics end up on the seafloor. Even though much attention is paid to plastics in the ocean gyres, they do not represent the final sink of most polluted plastics. Recent studies estimate that less than 1 % of plastic debris stays on the ocean surface and imply that the deep sea is the ultimate sink (Eunomia, 2016 and GRID Arendal). Tools for modelling the global transport and distribution of (micro)plastics are available for marine and freshwater systems (Lebreton, Greer & Borrero, 2012; van Sebille et al., 2015 and Kooi, Besseling, Kroeze, van Wezel & Koelmans, 2018). For instance, the Framework Programme 7 (FP7) CLEANSEA project developed a generic fate model that predicts an accumulation of microplastics in the Thames, the River Rhine estuary and along the Danish and German coast.

The atmospheric and terrestrial transport and deposition of microplastics, especially synthetic fibres, is an emerging area of research. Studies report an atmospheric fallout of 29-280 particles per m^2 per day, resulting in an annual deposition of 6-17 tonnes of fibres in the metropolitan area of Paris (Dris et al., 2015 and Dris, Gasperi, Saad, Mirande & Tassin, 2016). Information on terrestrial transport is scarce. Burial of conventional plastics used in agriculture, e.g. from mulching film, sewage sludge and composting, may occur and the mobility depends on the size of the plastics and characteristics of the soil (Hurley & Nizzetto, 2018 and Scheurer & Bigalke, 2018).

Plastic litter is not only subject to transport but also to degradation processes that change their physico-chemical properties. Physical forces (e.g. wave action and UV radiation), chemical reactions (e.g. hydrolysis and surface oxidation) and biological interactions (e.g. biofilm formation) drive the degradation of plastics (Andrady, 2011; Jahnke et al., 2017 and Rummel, Jahnke, Gorokhova, Kühnel & Schmitt-Jansen, 2017), see also Figure 3. These processes alter the transport, sorption and release of chemicals as well as the biological impacts of aged plastics. For example, the FP7 CLEANSEA and Horizon 2020 FreshwaterMPs projects reported the rapid sinking of microplastics that were supposed to be buoyant based on the polymers' densities. This indicates that sediments are the final sink of most degrading plastics. Polymer degradation also results in fragmentation, which generates smaller plastic items. Here, the H2020 FreshwaterMPs project demonstrated the formation of large quantities of nanoplastics from commodity plastics as well as bio-based and biodegradable plastics (Lambert & Wagner, 2016a and Lambert & Wagner, 2016b).

Characterising plastic debris relies on a generic workflow that is adapted to the respective compartment. In order to provide accurate information on the level of plastic pollution in a given ecosystem, plastics need to be sampled and separated from other materials as well as identified and characterised in terms of polymer types, shapes, sizes and other characteristics (see Table 1). First, sampling of aquatic systems is commonly performed using established (e.g. plankton nets and manta trawls) or new techniques (e.g. filters connected to pumps). Beach and other terrestrial litter is mostly collected manually, whereas sediments are sampled using corers or grabs. Sampling procedures are most advanced for microplastics in marine surface water. In a second step, the plastic particles

Figure 3: **Overview of factors influencing the weathering of plastics**


Factors influencing the weathering of plastic
Plastic Item
Plastic particle
Microplastic
Nanoplastic
Oligomers
Chemical fragments
Additives
Adverse effects
Biofilm formation
Vertical transport
Currents
Fragmentation and leaching
UV radiation
Salinity
Physical stress
Wave action
Biofilm formation
Microbial degradation
Fluctuating temperatures
Impacts on transport, fate and toxicity

Source: Jahnke et al., 2017

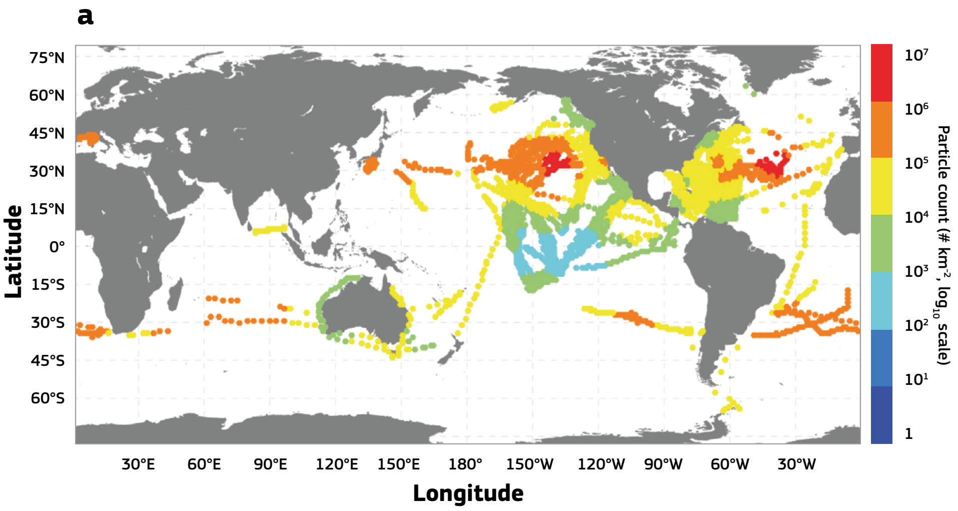
need to be separated from other materials. The aim of this sample preparation is to reduce the volume of the sample and separate plastics from other inorganic and organic matter in the sample. While this can be done manually for larger items, isolating microplastics is more challenging. Often, density-separation techniques to remove denser matter, combined with subsequent enzymatic or chemical digestion to remove organic matter are used to extract them from environmental samples. Third, sample analysis aims to correctly identify and characterise the plastic debris. This is crucial because visual analysis, especially of microplastics, can result in wrong estimates. For example, coloured cotton fibres may be mistaken for plastics, whereas white, black and translucent plastic fragments may be overlooked. Accordingly, more recent studies rely on advanced spectroscopic or spectrometric methods to verify the polymer type of the particles or the polymer content of a sample. As these methods are resource-intensive, low-cost methods have been developed, such as staining of plastics using hydrophobic dyes.

Much focus is put on developing and improving methods to analyse plastic debris. The FP7 CLEANSEA project, for instance, developed a sampling device for microlitter and macrolitter and found near-infrared spectroscopy suitable for monitoring marine litter. In the H2020 FreshwaterMPs project, a separation method for microplastics in freshwater samples was developed and validated. The FP7 COMMON SENSE project developed a microplastics sensor that can be integrated into a sensor platform for routine monitoring.

Table 1: **Overview of sampling and analysis methods for plastics in the environment**

	Sampling	Sample preparation	Analysis
Marine	- Manta trawls and plankton/bongo nets for water samples (Silva et al., 2018) - Corers and bottom trawls for sediments (Hanvey et al., 2017) and (Van Cauwenberghe, Devriese, Galgani, Robbens & Janssen, 2015)	- Visual collection for large items - Density separation using high-density liquids (saturated NaCl, NaI, $ZnCl_2$) to separate plastics from denser inorganic material - Removal of organic material using acids, bases, enzymes or peroxides	- Visual analysis of large items but also of microplastics - Spectroscopic techniques (FTIR and Raman) to identify the polymer type - Spectroscopy coupled with microscopy (μFTIR and μRaman) to analyse smaller particles (2-10 μm lower limit), automation with Focal Plane Array → particle concentrations - Mass spectroscopy (pyrolysis or TED GC-MS) → mass concentrations - Elemental analysis (ICP-MS or Energy-dispersive X-ray Spectroscopy; Silva et al., 2018 and Shim, Hong & Eo, 2017) - NIR spectroscopy for remote sensing - Dying with hydrophobic fluorophores (e.g. Nile red)
Freshwater	Similar methods, pump-filter systems used more recently	Similar to marine	Similar to marine
Terrestrial	Not advanced, manual sampling, crushing and sieving (Blasing & Amelung, 2018)	Similar to marine	Similar to marine
Biota	Mainly taken from monitoring campaigns or laboratory experiments (Lusher, Welden, Sobral & Cole, 2017)	Dissection or depuration, prior to the methods described above	Similar to marine
Challenges and limitations	- Often not validated using spiked samples, with recovery rates remaining unknown - Net sampling with large mesh sizes (usually 300 μm) neglects smaller particles	- Loss of particles due to filtration, adherence to material, lack of buoyancy (e.g. in NaCl) or destruction (e.g. acid labile polymers)	- Each technique has individual strengths and weaknesses - Visual approach results in misestimations - Spectroscopic tools are resource-consuming with low throughput, identification of weathered plastics challenging - Spectrometric tools do not provide particle concentrations, which are biologically relevant - General: tools for small microplastics and nanoplastics are lacking - Remote sensing tools are not yet a workable option
	- Contamination with microplastics possible and likely throughout the procedure - Often lack of adequate quality control		

Figure 4: Overview of plastic pollution around the globe



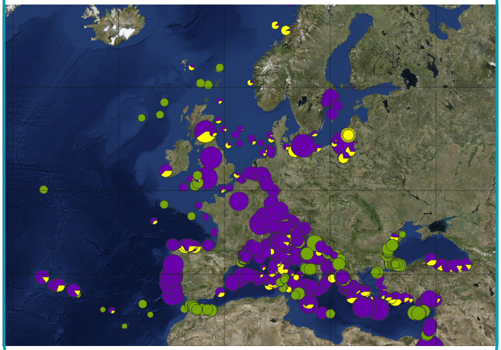
Source: Law, 2017

Numerous studies on the abundance of plastics debris, especially in the oceans, have established that plastic pollution is pervasive with even the remotest locations affected (Law, 2017), see also Figure 4. While concentrations vary locally, plastic debris has been found in the Arctic, the Antarctic, uninhabited islands and the deep sea (Peeken et al., 2018; Waller et al., 2017; Lavers & Bond, 2017; Pham et al., 2014 and Bergmann et al., 2017). Plastics represent the majority of marine litter on the ocean surface, on beaches and on the sea bottom. According to AWI's Litterbase database, 73 % of all items collected in 523 studies from 3 565 locations are plastics (AWI-Litterbase, 2018).

Nevertheless, based on current knowledge it is difficult to estimate the exact global scale of plastic pollution. The best available data based on 12 000 measurements from 26 studies on microplastics on the ocean surface indicated that between 15 and 51 trillion pieces or between 93 000 and 236 000 tonnes of microplastics float on the ocean surface (Law, 2017 and van Sebille et al., 2015). Another study included larger plastic items and estimated that a minimum of 5.25 trillion pieces of plastics, weighing 269 000 tonnes, is afloat at sea (Eriksen et al., 2014). While there is a lack of quantitative data on the amounts of plastic debris in the water column, seafloor and export to the shoreline, 9.4 million tonnes of plastics are expected to sink per year (Law, 2017 and Koelmans, Kooi, Law & van Sebille, 2017). Accordingly, the seafloor will be an important hotspot of plastic pollution.

Despite the availability of many case studies of Europe's regional seas and inland waters, so far there have been no comprehensive estimates on the scale of plastic pollution in Europe. AWI's Litterbase provides a repository of data on marine litter, including many European studies (Figure 5). A large-scale citizen science project found microplastics in beach sediments across 13 European countries. Concentrations ranged from 72 to 1 512 items per kg with a high spatial variability and higher levels found in the Eastern Mediterranean and Baltic Sea (Lots, Behrens, Vijver, Horton & Bosker, 2017). Studies on marine seafloor litter in European seas report between 0.2 and 32 items per hectare, over 70 % of them plastics (Pham et al., 2014 and Galgani et al., 2000). In total, it is estimated that between 75 000 and 300 000 tonnes of microplastics are released into the environment each year in the EU (European Commission, 2018j). A survey of floating litter in the Mediterranean Sea found between 5 and 49 macroplastic items per km^2 and estimated 62 million floating macrolitter items, including plastics (Suaria & Aliani, 2014). The FP7 CLEANSEA project conducted a seabed survey in the North Sea and Black Sea and found on average 4000 microplastics per kg sediment. Despite the absence of comparative data and systematic estimates on plastic pollution in Europe's environment, it is safe to assume that its scale is similar to other regions, especially given that a high population density is known to be a major driver.

Figure 5: Plastic litter in Europe (plastics in purple, size indicates levels)



Source: AWI-Litterbase, 2018

Challenges and knowledge gaps

Research is not focusing on the sources and fate of plastic pollution. Based on the state of play, current research focuses on describing the abundance of plastic pollution rather than on understanding its sources and the processes driving its fate. The major challenges are both scientific and institutional. Regarding the former, plastics leak from multiple, partly diffuse sources in techno-economical systems, again representing a complexity challenge involving multiple sectors and stakeholders. Concerning the latter, research on plastic pollution remains largely compartmentalised in the realms of marine sciences, which constrains the contribution of other disciplines that would otherwise enable a more effective investigation of the sources.

Scope and granularity of computational models are insufficiently developed. Whereas computational models exist to predict the spatiotemporal distribution of plastic debris in marine environments, this is largely lacking for freshwater, terrestrial and atmospheric compartments. In addition, models predicting the fate of plastics on a smaller spatial scale are less advanced. Modelling the distribution of plastics in the environment is crucial for predicting hotspots and sinks, and appropriate expertise exists in other areas (e.g. for natural particles) that could facilitate the development of computational models for plastic pollution.

Knowledge of the degradation of plastics in different environments remains limited. This is another key challenge that needs to be addressed to understand the distribution and impacts (Jahnke et al., 2017). Here, the difficulty is that the abundant information available from materials science, focusing on the use phase and on industrial waste management, cannot easily be translated into environmental scenarios. For instance, the term 'biodegradable', used in an industrial setting, has created the misconception that those plastics will also readily degrade in any other environment (Lambert & Wagner, 2017), see also Chapter 9. Accordingly, a better understanding of the factors affecting plastic degradation and its outcome, such as generation of nanoplastics and leaching chemicals, need to be understood more comprehensively.

Knowledge of the leaching of additives and other chemical classes is limited. The third aspect in terms of the fate of plastic pollution is the sorption and leaching of chemicals. While progress has been made in understanding these processes for persistent organic pollutants (POPs) in a marine context, major uncertainties exist regarding other chemical classes (e.g. pharmaceuticals and pesticides) that may be associated with plastic debris in other compartments (e.g. freshwater). The same is true for additives and other chemicals present in plastics, which remain largely unknown (see also Chapter 2), and thus their leaching under environmental conditions is not very well characterised. Accordingly, this gap in our knowledge prevents a comprehensive evaluation of the environmental relevance of plastic-associated chemicals. Ongoing work by the European Chemicals Agency (ECHA) on plastic additives could help fill this gap (Chemical-Watch, 2017; ECHA, 2016 and ECHA, 2018a).

Institutional and theoretical prerequisites for the comprehensive monitoring of plastic pollution are insufficient. Challenges in this regard include the lack of a common definition and categorisation framework for environmental plastic debris as well as the lack of harmonised and standardised sampling, analysis and reporting procedures, which leads to miscommunication. While some guidance for the monitoring of marine litter exists, the multitude of methodologies for quantifying plastics in the environment has resulted in a situation in which scientific data are often not comparable (Joint Research Centre, European Commission, 2013). The heterogeneous reporting, for instance in terms of concentration units (e.g. particles or mass per volume or area) exacerbates this situation. While there are calls to standardise many of these aspects on an international level, there is a risk that this will take time. As a result, the standardisation process may not keep up with and rather inhibit the constantly evolving science.

Analytical tools related to throughput, detection limits and precision are limited. While methods to analyse plastic debris, especially microplastics, are rapidly evolving, the current toolkit is limited in terms of sample throughput. Analysing very small plastics in complex environmental samples consumes many resources (technical equipment, time for measurement, data analysis). Compared to other spectroscopic methods, mass spectrometry provides a higher throughput but it cannot provide information on particle concentrations, which is required to assess the toxicity of small plastic items. Importantly, to date there is no reliable method to detect nanoplastics and tyre wear particles in the environment. In addition, the detection limits with regard to particle sizes and concentrations are limited, as is the capacity to detect plastics containing high amounts of additives (e.g. fillers and pigments) and degraded plastics.

Quality control and assurance is improving but still immature. In most published studies, the workflow of sampling, extracting and analysing plastics is not validated in terms of its recovery. Thus, it is not possible to evaluate the performance of a given method regarding its precision. At the same time, contamination during sampling, sample preparation and analysis remains a major issue due to the omnipresence of small plastic particles. More recent studies increasingly apply refined quality controls, including blank measurements to determine the level of background contamination. However, appropriate quality control and assurance measures are still immature and have not yet evolved into common scientific practice.

Current monitoring approaches only provide snapshots of a more complex situation. The mobility of plastics results in a dynamic distribution that varies in space and with time. These dynamics are not captured at present because reports on plastics in the environment often represent a single sampling campaign. In addition, studies with a longer time series that would enable the investigation of secular trends in plastic pollution remain scarce.

While there is broad acknowledgement that marine plastic pollution is pervasive and global, quantifying the scale of the problem remains challenging. It is clear that plastic pollution is ubiquitous, yet current research is still preoccupied with detecting and budgeting plastic litter floating on the ocean surface and beaches. Accordingly, data on plastics in the water column and the seabed is very limited.

Knowledge of the levels of contamination of inland waters and terrestrial ecosystems is scarce. Although it is widely acknowledged that the sources of plastic pollution are predominantly on land, knowledge thereof is scarce. This results in considerable uncertainties in the available estimates of the levels and loads of plastics in different ecosystems.

Data on the scale of plastic pollution in Europe is available but fragmented. From the scientific as well as the grey literature, it becomes clear that monitoring data, especially for microplastics, is available for a range of European seas, rivers and lakes. However, this information is fragmented and has not been aggregated so far. Accordingly, a comprehensive assessment of the scale of plastic pollution in Europe is absent.

With research focusing on microplastics, larger plastic debris is neglected. Knowledge of the scale of macroplastics in all compartments is limited. Accordingly, global and local estimates of the scale of the problem rely on fragmentary empirical data and tend to draw on information available from other sectors (e.g. waste management).

Policy recommendations and R&I priorities

Policy recommendations

Facilitate the development of a common framework to define and categorise plastic debris. A commonly accepted terminology is the prerequisite for data comparability, collaboration, meta-level analysis and assessment. Rather than continuing to have different organisations and bodies proposing their own definitions, a coordinated approach needs to be promoted. The agreed framework must cover parameters such as particle size, shape and composition. Because international standardisation efforts will take time, a pragmatic working definition for plastic debris could provide a valuable intermediate step.

Set up a regulatory framework of harmonised procedures to analyse plastic debris, including appropriate quality standards. Acknowledging that scientific methods and standards are constantly evolving, especially in a novel area such as plastic pollution, the advancement of these methods can be facilitated by promoting projects that benchmark and validate different available methodologies.

Develop a framework to ensure plastic pollution research and data gathering in a systematic and consistent way. With research on the scale of the problem rapidly evolving, a systematic collection of available data and a critical assessment are lacking. This can be overcome by providing guidance and infrastructure for data deposition in joint databases and by promoting meta-analysis of existing data, under the assumption that data is first made comparable and reliable. This synthesis of and reflection on available knowledge will significantly advance future research.

R&I priorities

Provide financial incentives for innovation in monitoring plastic debris in Europe's ecosystems. Given the limitations of current analytical methods, their efficiency needs to be improved to generate a more comprehensive understanding of the scale of pollution and to identify potential hotspots. This can be achieved by funding the (further) development of existing and new technologies to detect plastics, taking into account their heterogeneity in terms of materials. Emphasis should be placed on promoting high throughput and cost-efficient methods.

Provide funding to understand the sources, transport and distribution of plastic pollution. Comparative data on the contribution of point and diffuse sources, on transport pathways and on the scale of plastic pollution is needed, addressing different ecosystems, geographical areas and spatial scales. While this research is hard to do in detail on a global scale, case studies in selected areas can improve our understanding of the origin of plastic debris. This research should enable the development of appropriate and effective solutions. In addition to the sources, there is a need to understand the processes that drive the fate of plastic debris in different ecosystems and on different temporal-spatial scales. Here, computational models validated based on empirical data can help to predict hotspots and sinks of plastics. Such knowledge will support the identification of affected ecosystems and can guide mitigation measures.

Provide funding to understand the degradation of plastics in the environment, including the relevance of leaching chemicals. The degradation of plastics under environmental conditions cannot readily be predicted based on information available from materials science. Thus, degradation experiments simulating realistic weathering of plastics should provide insights into the fragmenting process of plastic debris as well as the release of chemicals. Such knowledge is key to assessing the environmental impacts of plastic pollution.

Provide funding to understand plastic pollution in commonly neglected compartments and ecosystems. Fund research generating knowledge about the scale of plastic pollution in the marine water column and the seabed as well as freshwater and terrestrial ecosystems. This will balance the understanding of plastic pollution, which is currently biased towards the sea surface and beaches.

1.2 Impacts of plastic pollution

State of play

In contrast to the ubiquity of plastic pollution, its impacts on biota and ecosystems are far from clear. Plastic debris can have direct effects on animals by inducing physical and chemical toxicity as well as indirect effects by changing habitat properties and transporting pathogens and invasive species. So far, most of the available data is on marine biota directly interacting with macroplastics in the field and on the toxicity of microplastics and nanoplastics in controlled laboratory studies. While these can in principle be used for an environmental risk assessment, it remains unclear whether existing frameworks (such as for chemical risks) can be applied. Besides knowledge gaps in the long-term ecological consequences of plastic pollution, the heterogeneity of plastic debris in terms of physico-chemical properties, such as diverse materials, chemical compositions, sizes and shapes, hampers such assessment (Kramm, Volker & Wagner, 2018; Backhaus & Wagner, 2018 and Amec Foster Wheeler Environment & Infrastructure UK Limited, 2017).

Nanoplastics, microplastics and macroplastics can induce direct impacts via physical interactions with biota. While external exposure, such as via entanglement, is relevant for macroplastics and often observed in the field, exposure via ingestion of microplastics has been experimentally demonstrated for a wide range of species. Similarly, exposure to nanoplastics may happen through transfer to tissues and cells.

- Exposure to macroplastics includes entanglement, smothering and ingestion and can result in reduced mobility, increased energy expenditure, reduced energy intake, injuries, and associated infections (Kühn, Bravo Rebolledo & van Franeker, 2015). As of 2015, more than 550 marine species have been affected by marine litter, including turtles, mammals and sea birds (Kühn, Bravo Rebolledo & van Franeker, 2015). One prominent example is ‘ghost fishing’, i.e. animals being trapped in derelict fishing gear. According to a review, over 5 400 individuals from 40 species of marine mammals, reptiles and elasmobranchs have been recorded to have been entangled through ghost fishing (Stelfox, Hudgins & Sweet, 2016). The majority of entanglements ultimately result in mortality, as for instance observed for sea turtles (Duncan et al., 2017).

- Microplastics can have similar physical impacts to macroplastics (Wright, Thompson & Galloway, 2013). However, attachment to external and internal absorptive surfaces is likely more relevant. One such example is the attachment of microplastics to the gills of shore crabs, which reduces their oxygen consumption (Watts et al., 2014 and Watts et al., 2016). More data is available on the ingestion of microplastics. While ingestion does not represent a toxicological hazard per se, the idea is that ingested microplastics may reduce the food intake and in extreme cases block the digestive system (i.e. obliteration). In addition, particles can attach to epithelia, and thereby reduce the available area for food adsorption. In both cases, microplastic intake can decrease nutrient assimilation and thus energy intake. For instance, microplastic exposure reduced feeding activity and energy reserves in lugworms (Wright, Rowe, Thompson & Galloway, 2013). This may have downstream effects on the life cycle of the organism, including reduced growth or reproduction, as for example shown in the Pacific oyster (Sussarellu et al., 2016).

- Very small microplastics and nanoplastics may pass biological barriers and can become internalised in tissues or cells. The first indications of this effect came from studies on Blue mussels, in which microplastics were retained in the circulatory system for over 48 days and translocated to tissues, inducing inflammatory responses (Browne, Dissanayake, Galloway, Lowe & Thompson, 2008 and von Moos, Burkhardt-Holm & Kohler, 2012). More recent studies report tissue translocation of nanoplastics or microplastics in nematodes, barnacles, daphnids, mussels, crabs and fish (Zhao, Qu, Wong & Wang, 2017; Bhargava et al., 2018; Brun, Beenakker, Hunting, Ebert & Vijver, 2017; Rosenkranz, Chaudhry, Stone & Fernandes, 2009; Magni et al., 2018; Ribeiro et al., 2017; Watts et al., 2014; Watts et al., 2016; Farrell & Nelson, 2013; Mattsson et al., 2017; Collard et al., 2017 and Skjolding et al., 2017). Microplastics entering tissues can cause internal injuries, which may induce further downstream effects such as inflammation or necrosis. In addition, effects at a cellular level have been found, such as changes in gene expression (Balbi et al., 2017 and Torre et al., 2014).

Besides physical impacts, additional chemical exposure of animals in contact with plastics has been hypothesised to drive toxicity. In addition to their polymer backbone, plastics contain other chemicals used in their production. These includes starting compounds and monomers, catalysts, solvents and additives as well as non-intentionally added substances (see also Chapter 2). Here, monomers such as bisphenol A (BPA), and plastic additives, especially plasticisers such as phthalates, receive most attention, probably because of their known human toxicity. Importantly, each finished plastic product will consist of a complex chemical mixture with an individual chemical formulation. In addition to the chemicals used in the manufacturing of synthetic polymers, plastics are mostly hydrophobic, and thus able to sorb chemicals from the surrounding compartments. Accordingly, they will accumulate pollutants from the environment. Early studies reported orders of magnitude higher concentrations of POPs sorbed to plastics compared to seawater (Teuten et al., 2009). In addition, smaller plastic items will take up proportionally more chemicals than larger items because of their larger surface to volume ratio. This gave birth to the idea that plastics, especially microplastics, will transfer chemicals either from the product or the environment to the exposed organism. Once ingested, the change in the milieu will result in increased desorption of plastic-associated compounds and a corresponding increase in chemical exposure. In turn, this process – coined vector or Trojan horse effect – may induce chemical toxicity, resulting for instance in endocrine disruption (Syberg et al., 2015; Rochman C. M., 2013 and Koelmans, Besseling & Foekema, 2014).

The impact of chemicals leaching from plastics strongly depends on the concentration of chemicals in the plastic item and on the substances already present in the organism and the surrounding compartment. Accordingly, microplastics loaded with chemicals and ingested by a 'pristine' organism might result in the transfer of chemicals (Batel, Borchert, Reinwald, Erdinger & Braunbeck, 2018 and Batel, Linti, Scherer, Erdinger & Braunbeck, 2016). On the other hand, virgin plastics ingested by a polluted organism may have a cleansing effect. While there is no scientific consensus on the biological relevance of the vector effect, it needs to be evaluated in the context of natural particulate matter, which is abundant in natural environments. In view of this, the contribution of chemicals released from microplastics is considered low (Koelmans, Bakir, Burton & Janssen, 2016). With regard to macroplastics, the leaching of chemicals has been less studied but may be especially relevant at hotspots of plastic pollution, such as in the vicinity of open landfills.

In addition to direct physical and chemical effects, plastic debris can have more indirect, systemic impacts. Multiple experimental studies demonstrate the trophic transfer of microplastics, i.e. its transmission from prey to predator, and suggest that they can move across food webs (Carbery, O'Connor & Palanisami, 2018; Vethaak & Leslie, 2016 and Rochman, Hoh, Kurobe & Teh, 2013). However, this mostly represents a gut-to-gut transfer, which means that bioaccumulation as shown for POPs has not been observed. Similarly, no information is available on whether microplastics bioconcentrate, and the biological relevance of trophic transfer remains unknown. There is also little empirical evidence available on how plastic pollution may change habitat properties and structures. Examples include shading effects and changes in sediment properties (Green, Boots, Blockley, Rocha & Thompson, 2015). Finally, plastic pollution may increase disease incidence on an ecosystem level, as recently shown for coral reefs, and facilitate the spread of invasive species and pathogens (Lamb et al., 2018; Rech, Borrell Pichs & Garcia-Vazquez, 2018 and Kirstein et al., 2016).

Driven by the omnipresence of microplastics, the public is concerned about potential human health impacts, while scientific knowledge remains scarce. This is especially true for seafood and fish, which may be contaminated with microplastics via food web transfer (see above). So far, research has focused on oral exposure to nanoplastics and microplastics through food consumption. In contrast to dietary sources, little information is available on inhalation of airborne plastics and dermal exposure. While knowledge of the health effects of other inhaled airborne particles is abundant, the toxicity and toxicokinetics of nanoplastics and microplastics remains largely unknown (European Food Safety Authority CONTAM Panel, 2016).

Human exposure to microplastics can occur through inhalation of plastic particles and fibres. The exposure to carbon-based fibres via indoor air ranges from 9 000 to 20 000 fibres per m^3 (Schneider et al., 1996). Occupational exposure in textile manufacturing appears to result in much higher concentrations, with levels up to 1 million polyester fibres per m^3 (Wright & Kelly, 2017). Dermal exposure to microplastics is unlikely as intact human skin is largely impermeable to particles down to a few nanometres is size (Cevc & Vierl, 2010). The question of whether small nanoplastics – as recently detected in personal care products – can pass through the skin remains unanswered so far (Hernandez, Yousefi & Tufenkji, 2017).

Oral exposure to microplastics can occur via contaminated foodstuff and water. Microplastics have been detected in fish and seafood (see (Food and Agriculture Organization of the United Nations, 2017) for review), drinking and bottled water, honey, beer and table salt (Ossmann et al., 2018; Schymanski, Goldbeck, Humpf & Furst, 2018; Kosuth, Mason & Wattenberg, 2018; Liebezeit & Liebezeit, 2013; Liebezeit & Liebezeit, 2014; Iniguez, Conesa & Fullana, 2017; Karami, et al., 2017 and Yang et al., 2015). While existing quality standards need to be further improved, these findings first and foremost highlight the omnipresence of plastic particles in food and beverages. The European Food Safety Authority (EFSA) has emphasised that data on the microplastic content of food is still scarce and used mussel consumption to estimate human exposure (European Food Safety Authority CONTAM Panel, 2016). Accordingly, eating one portion of mussels will result in an uptake of 900 particles representing approximately 7 µg plastic. In this conservative scenario, the release of accumulated POPs would be negligible, increasing the overall exposures by a maximum of 0.006 % (European Food Safety Authority CONTAM Panel, 2016). Similarly, the additional exposure due to leaching of plastic additives is considered low (Food and Agriculture Organization of the United Nations, 2017).

The important question is whether ingested nanoplastics and microplastics stay in the digestive system or can translocate to other parts of the body. Particles < 150 µm in size can pass through biological barriers via different mechanisms (Wright & Kelly, 2017 and Geiser et al., 2005). The particle's size, shape and surface properties affect its potential to transfer to tissues and a wealth of information is available on these processes in mammalian models but not in humans (see references in European Food Safety Authority CONTAM Panel, 2016 and Wright & Kelly, 2017). In contrast, the distribution of plastic particles after absorption is poorly understood. As relevant toxicity data were absent, EFSA concluded that it is currently not possible to evaluate the human health risk of nanoplastics and microplastics (European Food Safety Authority CONTAM Panel, 2016). A recent study exposing rats to nanoplastics did not report significant effects on behaviour or body weight (Rafiee et al., 2018). Another study in mice, however, showed that 5 and 20 µm microplastics are widely distributed in tissues and induced metabolic changes and oxidative stress (Deng, Zhang, Lemos & Ren, 2017). In addition to these effects, translocating plastic particles are mainly thought of as inducers of immune responses and inflammation, which may ultimately result in adverse downstream effects. However, the toxicity of plastics will – as in the case of non-human animals – depend on a range of material properties, with surface reactivity, complex morphologies and stability of the particles being key aspects (Galloway T., 2015).

Despite the apparent knowledge gaps regarding the potential health implications of plastic pollution, lessons should be learned from similar challenges in other domains. The impacts of nanoplastics and microplastics should be assessed drawing on existing insights from particulate matter toxicology concerning nanomaterials, air pollution, fibre toxicity and abrasion from prosthetic implants (Rist, Carney Almroth, Hartmann & Karlsson, 2018). In addition, concerns about exposure via seafood and fish need to be balanced against other sources of exposure from the everyday use of plastics, which are likely to be more relevant but so far poorly understood (Rist, Carney Almroth, Hartmann & Karlsson, 2018). Importantly, a more comprehensive debate is needed and must also include chemical exposure from plastic products in use, notably microplastics (see Chapter 2).

Plastic pollution can have multiple socio-economic impacts, ranging from direct financial losses in a range of sectors to a decrease in ecosystem services that entails indirect costs. In addition, plastic pollution touches on an aesthetical and ethical dimension, which is difficult to quantify yet relevant. Similar to the quantification of marine plastic pollution, most of the information available is on the socio-economic consequences of plastic debris in the oceans.

UNEP has estimated that the total natural capital costs of plastics in the consumer goods industry are USD 75 billion, 40 % of this located in the food, soft drink and non-durable household goods sectors (United Nations Environment Programme, 2014). Interestingly, over 75 % of the known and quantifiable impacts associated with plastic use were allocated to the upstream portion of the supply chain (raw materials to feedstock). The report also highlights the issue of externalising natural capital costs. In fact, if the upstream impacts of plastic were paid for in full by businesses, the price of plastics would increase by 44 % on average (United Nations Environment Programme, 2014). As for the impacts of plastics on marine ecosystems, UNEP has estimated a total weighted natural capital cost of USD 13 billion (United Nations Environment Programme, 2014). Accordingly, plastics in the oceans contribute a non-negligible 17 % to the total life-cycle impacts, with non-durable household goods, clothing and accessories, and soft drink goods contributing most. The impacts vary across regions, with lower downstream costs in North America, Europe and Oceania compared to Africa and Asia. Interestingly, Europe sees the second highest natural capital impacts (USD 22 billion) after Asia. Comparing plastics to a mix of alternative materials fulfilling the same purpose, a report by Trucost conducted for the American Chemistry Council concluded that the alternatives would lead to an even higher net environmental cost, and that the impacts of plastics could be further lowered (TruCost, 2016).

Focusing on the plastic packaging sector, it has been estimated that 95 % of the material value, translating into USD 90-120 billion, is lost to the economy annually after a typical short use cycle (World Economic Forum, Ellen MacArthur Foundation and McKinsey & Company, 2016). This loss is related to the low global recycling rates (14 %) and value loss during the collection, sorting and recycling processes, with only 5 % of plastic packaging material value retained. Even for PET, which is recycled the most effectively, only 7 % is recycled bottle-to-bottle. A global flow analysis in the same study indicates that while only 2 % of plastic packaging is recycled in a closed loop that retains sufficient quality, 40 % is landfilled and 32 % leaks into the environment. This leakage generates significant negative externalities regarding the degradation of natural ecosystems. Based on the UNEP estimates, plastic packaging contributes USD 40 billion to the total natural costs of plastics, outweighing the profits of the packaging industry (United Nations Environment Programme, 2014).

In addition to these global assessments, the socio-economics of beach litter has been investigated in more detail with regard to the tourism industry and clean-up costs. The social sciences have established a negative link between the amount of beach litter and beach visits (Brouwer, Hadzhiyska, Ioakeimidis & Ouderdorp, 2017). In South Africa, for instance, 10 litter items per m^2 deter 40-60 % of tourists (Ballance, Ryan & Turpie, 2000). A spill of landfilled litter in New York and New Jersey reduced beach visits by 8-33 %, resulting in economic losses of USD 0.38-1.87 billion (Ofiara & Brown, 1999). In Europe, the local authorities international environmental organisation KIMO has estimated that the annual costs for removing beach litter are EUR 18 million in the UK and EUR 10.4 million in the Netherlands and Belgium (KIMO, 2010). Research from the FP7 CLEANSEA project investigated the social cost of litter on European beaches and found that about half the tourists in Bulgaria, the Netherlands and Greece are willing to participate in beach clean-ups, whereas 70 % of respondents would stop visiting littered beaches (Brouwer, Hadzhiyska, Ioakeimidis & Ouderdorp, 2017). While the loss of plastics is limited in Europe, the estimated costs of cleaning up marine litter in coastal areas can amount to up to EUR 630 million per year (European Commission, 2018c).

Marine plastic debris can directly and indirectly affect a range of sectors and societies in a larger context. There can be a direct impact on fishery, aquaculture, agriculture, energy and shipping sectors through blockage or damage of infrastructure, such as drains, pipes, cages, gear and ships (NOLAN-ITU, 2002 and Galgani et al., 2010). For example, incidents with fouled propellers and blocked intake pipes of fishing vessels have cost the Scottish fishery industry EUR 12-13 million (KIMO, 2010). Using the Shetland Islands as a case study, KIMO further estimated that the total costs of marine litter across sectors aggregates to EUR 1-1.1 million per year, suggesting that the economic impact on coastal communities in the Northeast Atlantic region is probably very high (KIMO, 2010). In total, marine litter costs the fishing fleet of the European Union an estimated almost EUR 61.7 million annually or 0.9 % of total revenues (United Nations Environment Programme, 2016). Indirect impacts can, for example, occur due to a reduced consumption of seafood based on the perceived risk of microplastic contamination or a decline in commercially relevant fish species due to ghost fishing (GESAMP, 2016). As one of the few available examples shows, removing 10 % of derelict fishing pots would provide estimated additional revenues of USD 831 million annually for the global crustacean fishery industry (Scheld, Bilkovic & Havens, 2016). In addition, there may be more subtle impacts of plastic pollution on ecosystem services. For instance, plastic mulching in agriculture may promote soil degradation and reduce soil biodiversity (Steinmetz et al., 2016 and Schirmel, Albert, Kurtz & Muñoz, 2018). Accordingly, terrestrial hotspots of plastic pollution may experience similar effects on soil quality, and thus eventually on primary production and food supply.

Plastic pollution may also be linked to human well-being. Plastic debris results in a loss in recreational value (e.g. through beach litter), potentially depleting psychological restoration of humans in natural environments. In this regard, behavioural studies have shown that marine litter can undermine the psychological benefits normally experienced at the coast (Wyles, Pahl, Thomas & Thompson, 2016). More direct impacts on human health and safety may occur via accidents resulting in costs for medical treatment (GESAMP, 2016). In terms of pest control, it is well known that plastic litter provides breeding sites for pathogen-transmitting insects, such as *Aedes albopictus*, and may therefore facilitate the spread of the West Nile and dengue virus (Simard, Nchoutpouen, Toto & Fontenille, 2005). Finally, plastic pollution inflicts a loss on the intrinsic value of nature, and thus depletes important cultural services provided by an ecosystem. Eventually, this also touches on larger moral issues concerning the relationship between societies and the environment, which so far remain understudied.

Challenges and knowledge gaps

Several important knowledge gaps exist regarding the human and environmental health impacts of microplastics and nanoplastics, which hampers effective risk assessment and risk management (Galloway T., 2015; Wright & Kelly, 2017; Gallo et al., 2018; Hermabessiere et al., 2017 and Rist, Carney Almroth, Hartmann & Karlsson, 2018). The most important information requirements address the types of exposure sources, human exposure routes, as well as levels of exposure in humans and the environment, and hazard characterisation (European Food Safety Authority CONTAM Panel, 2016). Besides this knowledge gap, the major challenge here is the heterogeneity of plastics in terms of physico-chemical properties. While it will not be viable to assess all types of plastic debris, key properties driving the toxicity (e.g. a specific size range or shape) are currently poorly understood. Similarly, which species and habitats are susceptible is unknown and the impacts of plastics on them may be different to that found in research relying on standard animal models.

It is uncertain whether current experimental models and methodologies are adequate for predicting the impacts of plastics on the environment. In that sense, the debate on the environmental relevance of toxicity testing of microplastics is interesting. While it currently largely focuses on discussing the need for testing ‘environmentally realistic’ concentrations of plastics, the larger question is whether our experimental models designed and optimised for dissolved chemicals are adequate for testing particles. This is not only true for plastics as a stressor but also for their potential long-term ecological impacts.

Empirical research on impacts of macroplastics is limited. Despite multiple case reports of the negative impacts of macroplastics on marine life, little empirical research has been performed so far to understand and quantify the impacts of plastic pollution on populations and communities. Thus, we need ecological research to eventually determine if and how plastics ultimately contribute to the larger issue of global change.

The existing knowledge is too preliminary to evaluate the environmental risks of plastics. Despite the fact that there is abundant evidence from case reports that macroplastics physically harm marine life, the scale of these impacts in terms of incidence and affected populations remains largely unclear. Similarly, controlled laboratory studies demonstrate negative impacts of microplastics on a broad range of species. However, toxicity is mainly induced by very small particles at very high concentrations currently not detected in the environment (Lenz, Enders & Nielsen, 2016). Ignoring obvious gaps in our knowledge – especially regarding the environmental levels of very small particles, their heterogeneity and more long-term ecological effects – this has sparked an ongoing debate on the ‘environmental relevance’ of microplastics (Lambert, Scherer & Wagner, 2017; Burton, 2017 and Kramm, Volker & Wagner, 2018). Leaving aside this discourse, a preliminary risk assessment based on the available data on the toxicity and levels of freshwater microplastics indicates that the margin of safety is very low.

Accordingly, a numerical environmental risk estimate for a business-as-usual scenario, based on the existing assessment concept for chemicals, will be calculated in the near future (Backhaus & Wagner, 2018).

A comprehensive understanding of the social drivers and implications of plastic pollution is lacking. Research on plastic pollution happens largely in the realm of natural sciences. However, it is apparent that its root causes are social, as are its negative impacts. While existing research demonstrates that the latter are already manifesting in a range of sectors of the socio-economic system (e.g. tourism), the social drivers and societal implications of plastic pollution have not been comprehensively addressed. However, understanding both is critically important for developing effective solutions, performing a cost-benefit analysis to decide on these and for creating societal acceptance of change (see also Chapter 6). The Group of Chief Scientific Advisors of the European Commission is investigating the impacts of microplastic pollution, including those relating to social and legal sciences, to present the available evidence in a way that promotes a more informed public and policy debate (Group of Chief Scientific Advisors, European Commission, 2018).

The plastic pollution problem and related research activities are not structured through a systemic lens. It is important to acknowledge that the scientific study of plastic pollution is still in its infancy. At the same time, plastic pollution is a ‘wicked problem’ involving multiple, highly interconnected and interdependent drivers and impacts (Kramm, Volker & Wagner, 2018 and Peters, 2017). Thus, it is not surprising that many knowledge gaps exist. The immense public concern has induced a massive expansion of research on plastic pollution, especially on microplastics. However, the problem formulations as well as current research activities are still often badly structured. Importantly, a lack of problem-structuring and systematic analysis is also preventing an assessment of the risks plastic pollution may pose to the environment and human health. Risk assessment frameworks developed to evaluate the safety of chemicals cannot easily be translated to plastic debris, especially given the plethora of materials and forms of plastics that come under this umbrella term. So far, new approaches on how to assess the risks of plastic pollution are lacking, yet they are needed to move forward with science-based decision-making.

A systematic appraisal of the state of the science is lacking. Despite the publication of many review and opinion papers, well-structured and quantitative assessments are lacking. For instance, a comprehensive understanding of the risks associated with the scale of plastic pollution, its sources and its impacts would require systematic reviews and meta-analysis. Importantly, plastic pollution needs to be placed and evaluated in the larger context of global change.

Policy recommendations and R&I priorities

Policy recommendations

Facilitate collaboration to ensure systematic analyses of existing information on plastic pollution, and discussion about innovative experimental approaches. Collaboration platforms for knowledge transfer should spur discussion within and beyond academia. To facilitate advancement of the research area, systematic reviews and quantitative meta-analysis need to be promoted. This is crucial to identifying knowledge gaps and thereby guiding research. It should also facilitate debates on innovative approaches, e.g. to estimate the ecological impacts of plastics.

Develop and implement a risk assessment framework that considers the heterogeneity of plastic debris as well as potential ecological and societal impacts. Simply adopting methods and frameworks from chemicals testing to assess the risk of plastic pollution may be inadequate. Therefore, it is vital to support research and discussion that critically revisits and thereby advances current practices.

Develop and implement frequent benchmarking of plastic pollution in the context of other drivers of global change. To allocate societal resources appropriately and responsibly, we need to understand the contribution of plastic debris to global change, taking into consideration the impact of other important drivers, such as global warming, habitat destruction and biodiversity loss.

R&I priorities

Provide funding to understand the toxicity and ecological impacts of plastic debris, including on public health. Given the diversity of plastic debris, funding research into which material properties drive the toxicity and which species and human populations are susceptible is key. This knowledge is critical in assessing the risks of plastics and can act as a driver of innovation in a safe-by-design and green chemistry context.

Provide funding for transdisciplinary research on plastic pollution by including social and behavioural sciences. A 'wicked problem' can neither be understood nor solved by one individual discipline – a systemic approach is needed. Social and behavioural sciences can play a key role here in uncovering the social drivers and impacts of plastic pollution. Likewise, a transdisciplinary approach needs to include economics, law, polymer chemistry and materials science. The work carried out by the Group of Chief Scientific Advisors can provide further background and direction as it intends to produce a Scientific Opinion on the health and environmental impacts of microplastic pollution (Group of Chief Scientific Advisors, European Commission, 2018).

1.3 Solutions to eliminate or minimise plastic pollution

State of play

As plastic pollution emerges as a global challenge, public concerns have created pressure to act. Accordingly, a plethora of solutions to prevent or mitigate plastic pollution, especially in the oceans, has been proposed and partly implemented so far. These actions include end-of-pipe clean-up activities to remove plastic litter from beaches and the ocean surface (see examples below), and proposed bans of certain plastic products, such as microbeads in cosmetics and single-use plastic straws (ECHA, 2018b and European Commission, 2018o). More comprehensive policy measures are proposed too, as for example laid out by the European Plastics Strategy (European Commission, 2018j).

The current approaches to mitigate plastic pollution are legitimated by informed precaution rather than a stringent evidence-based risk assessment. There are good reasons to apply the precautionary principle to the issue, with the ubiquity, persistence and probably increasing emissions of plastic debris as major arguments (United Nations Environment Programme, 2016). Similar arguments have led researchers to call for plastic debris to be included in the frameworks of hazardous waste, POPs as well as planetary boundaries, implying a need for international action (Rochman et al., 2013; Worm, Lotze, Jubinville, Wilcox & Jambeck, 2017; Villarrubia-Gómez, Cornell & Fabres, 2017 and Borrelle et al., 2017). A precautionary approach to plastic pollution has several advantages: it is proactive and enables one to move forward with solutions in the light of scientific uncertainty (Table 2, Mee, Jefferson, Laffoley & Elliott, 2008). While a precautionary approach appears to be favoured by many scientists, it remains unclear if this is the consensus.

Table 2: Comparison of alternative visions for achieving Good Environmental Status (GEnS)

	Evidence-based action (comprehensive understanding of the system)	Precautionary approach (removal of all tangible threats)
Advantages	Reduces scientific uncertainties Attractive to legislators and industry	Anticipatory; acknowledges the scientific uncertainty Ensures capacity to adapt to unforeseen problems
Disavantages	Science and information base may be insufficient Reactive Costs of monitoring are high and require long-term government buy-in	A hard sell as costs of implementation may be high Difficult to assess areas where precaution is warranted Makes an assumption that impacts are inevitable
Public face	Science-based indicators often difficult to understand	Public may seek alternative products and services when costs spiral

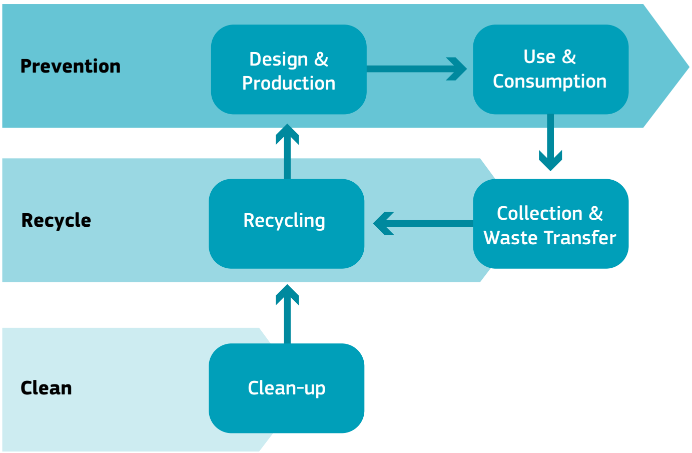
Source: Mee, Jefferson, Laffoley & Elliott, 2008

Some researchers have argued for a strictly evidence-based approach, especially with regard to microplastics in personal care products (Burton, 2017). Such a reactive approach relies on a comprehensive understanding of the problem, which will feed into a risk assessment that considers the probability and the hazards of plastic pollution (United Nations Environment Programme, 2016). Given the apparent knowledge gaps, such an approach is not implementable at present and the time it takes to fill these gaps may increase the costs of inaction (Kramm, Volker & Wagner, 2018).

Growing scientific knowledge needs to inform the development and choice of solutions. Taking a precautionary approach to plastic pollution does not make science obsolete (Mee, Jefferson, Laffoley & Elliott, 2008). However, it makes it necessary to shift focus from the current status quo of investigating the problem towards more solution-oriented research. Chemical risks represent a similar challenge and, using BPA as an example, it has been argued that '[r]ather than simply characterising problems in great detail, the scientific community can use its tools and resources to prioritise chemicals of concern in a more efficient manner as well as characterise solutions' (Tickner, 2011). In terms of plastic pollution, this implies that better knowledge can be used to prioritise sources of plastic debris as well as types of materials and products according to their impact, to promote the development of safer alternatives and to benchmark the performance of existing and future solutions.

Principles reflecting systems thinking should guide the implementation of solutions. With a public debate centring on the pollution aspect of plastics, much focus is put on removing plastic debris from natural environments. While this may have certain benefits in terms of creating awareness, clean-up measures are the least effective solution when considering the waste hierarchy (see Figure 6). Solutions should reflect an understanding of the entire plastics system, and how the different stages of design, production, use and after-use handling affect one another. Such understanding will automatically lead to actions upstream in the value chain, such as innovative product design that changes citizens' behaviour or is more suited for recycling. The FP7 CLEANSEA project developed a set of policy options for a litter-free sea and emphasised that 'priority should be given to those

Figure 6: Schematic overview of solutions to plastic pollution



Source: Adapted from FP7 CLEANSEA

stages that lead to waste prevention (in terms of reduction and preparation for re-use)' (Veiga et al., 2015). This includes two approaches: the 'prevention of plastic production and prevention of plastic becoming waste. These two sub-levels feed into each other: if less plastic is produced then less plastic becomes waste. If less plastic is thrown away through reuse or recycling, then potentially there is less demand for virgin plastic and production decreases' (European Commission, 2011b).

While solutions to plastic pollution are available across the whole life cycle, currently most focus is placed on the after-use phase. This includes initiatives to remove plastic debris from the ocean surface (e.g. the Ocean Cleanup Project) and shorelines (e.g. the International Coastal Cleanup). Other initiatives target lost and abandoned fishing gear in particular (e.g. the Healthy Seas Initiative in Europe). In addition, litter is removed from rivers and harbours using technical barriers, e.g. Mr. Trash Wheel in Baltimore, and some organisations run programmes to rescue marine wildlife entangled in plastics, e.g. British Divers Marine Life Rescue.

Clean-up activities remove a large amount of debris, but their efficiency is far from clear. For example, almost 800 000 volunteers removed about 20 million pieces of litter weighing roughly 9 300 tonnes during the 2017 International Coastal Cleanup (Ocean Conservancy, 2018). In terms of practicalities, cleaning up litter along coastlines is a preferable option (GESAMP, 2016). Even though only 5 % of marine plastic litter accumulates there, the litter concentrations are much higher on beaches (2 000 kg per km^2) than on the sea surface (< 1 kg per km^2) or the seabed (70 kg per km^2) (Eunomia, 2016). However, scientific knowledge of how to best organise beach clean-ups is lacking and it is necessary to understand the residence times of litter on the beach, the period with the highest litter inputs from the sea and the time when most litter has accumulated (Kataoka & Hinata, 2015). Similarly, there is a lack of comprehensive data on the effectiveness and efficiency of clean-up operations (GESAMP, 2016). Research on daily clean-ups by local authorities suggests that large litter is effectively removed but smaller items remain on the beaches (Loizidou, Loizides & Orthodoxou, 2018). With regard to microplastics, GESAMP concludes that clean-up actions are 'unlikely to be cost-effective, underlining the need for upstream preventative measures on sources' (GESAMP, 2016).

While they bring additional benefits regarding public awareness and environmental citizenship, clean-up measures have also been criticised as being misguided because they address the symptoms instead of the sources of plastic pollution. For example, the Ocean Cleanup Project's plan to collect plastics floating in the North Pacific Gyre has been criticised for being inefficient in terms of removal and costs, technically immature and potentially harmful to marine life. More importantly, some consider cleaning up plastic debris in the oceanic gyres 'a distraction' from true solutions, which are considered to be located upstream (Stokstad, 2018). These valid arguments notwithstanding, clean-up activities have benefits beyond efficiency in that they promote public awareness and strengthen environmental citizenship. A recent behavioural study showed that participants in beach clean-ups perceived this activity as more meaningful than others and learned more about the environment. The benefits of clean-ups in terms of individuals' education and well-being may thus induce further environmental benefits in the future (Wyles, Pahl, Thomas & Thompson, 2016 and Wyles, Pahl, Holland & Thompson, 2017).

A plethora of other solutions is available for targeting multiple sources, life stages, stakeholders and geographical areas. While the discussion in the arena of environmental sciences still focuses on the removal and prevention of marine litter (Löhr et al., 2017), there is growing awareness that the solutions to this 'tragedy of the commons' need to be systemic (Vince & Hardesty, 2018). Accordingly, mitigation measures can be aligned to the different life stages of plastics (see Table 3), to the waste hierarchy and to policy levels or they can address global governance, developing economies, the plastics economy in general and microplastics in particular (Eriksen, Thiel, Prindiville & Kiessling, 2018; United Nations Environment Programme, 2014; World Economic Forum, Ellen MacArthur Foundation and McKinsey & Company, 2016; United Nations Environment Programme, 2016; European Commission, 2011b; Sebille, Spathi & Gilbert, 2016; Brennholt, Heß & Reifferscheid, 2018; Ocean Conservancy, 2015 and Eunomia, 2018). Compared to the early literature, the development and assessment of potential solutions is rapidly evolving. More recent publications address the issue more systemically, taking into account the plastics life cycle, comparing different sources and performing cost-benefit analysis (Sebille, Spathi & Gilbert, 2016 and Ocean Conservancy, 2015 and Eunomia, 2018). Importantly, '[t]here is no "silver bullet" or single approach that will effectively resolve this complex environmental and societal challenge. Instead, an ever-changing variety of actions, activities, legislative and cooperative approaches will ultimately help resolve this tragedy of the commons that plastic pollution has become' (Vince & Hardesty, 2018).

Waste management remains another priority for reducing plastic pollution. This is motivated by the fact that mismanaged waste is a major contributor to land-to-sea litter and potentially also to land-to-land litter (Jambeck et al., 2015). In developed economies with efficient waste management systems, the current discussion focuses on improving wastewater treatment to remove microplastics. State-of-the-art wastewater treatment plants (WWTPs) remove between 83 and 99.9 % microplastics from the liquid sewage stream, even when taking account very small particles (Prata, 2018 and Simon, van Alst & Vollertsen, 2018). However, due to the large volumes of water these facilities treat, the total load of residual microplastics released into the environment can be high. For example, despite a removal efficiency of 99.3 %, all Danish WWTPs have been estimated to emit 3 tonnes of microplastics annually (Simon, van Alst & Vollertsen, 2018). Extrapolations like these have resulted in the widely held view that WWTPs are a relevant source of microplastics – technically they are entry points – and in calls for implementing additional technical barriers. While there is little research available, the installation of advanced technologies at the end of the treatment process, including membrane bioreactors, sand filters and dissolved oxygen flotation, may further improve the removal effectiveness (Talvitie, Mikola, Koistinen & Setala, 2017). However, upgrading WWTPs brings additional economic and environmental costs (investment, greenhouse gas (GHG) emissions, etc.) that need to be factored in when deciding on such technical measures. In addition, combined sewer overflows may be more relevant in terms of their emission of plastics, even though quantitative data is absent. This highlights once again the importance of benchmarking the different sources and transport pathways of plastic debris.

Another aspect dominating the discussion on waste management is the release of synthetic fibres during textile washing. Research on the shedding of synthetic fibres during clothes washing found up to 6 million fibres released from a single load (Cesa, Turra & Baruque-Ramos, 2017). As with wastewater, extrapolation to a national scale results in large emission estimates. For instance, the Finish population generates between 154 and 411 tonnes (1-5 x 10^{14} fibres) polyester and cotton fibres annually, not taking into account the removal by WWTPs (Sillanpaa & Sainio, 2017). The removal of fibres during washing could be achieved by developing washing machines with a built-in effluent filter or using in-drum devices to capture fibres (Eunomia, 2018). While the latter are already on the market, their efficiencies and those of filtering methods are not known. Interestingly, the washing conditions appear to affect the shedding of fibres. For instance, top-load machines generate microfibre masses that are about seven times higher than front-load machines (Hartline et al., 2016). Other relevant parameters include the use of detergent and surfactant as well as the washing temperature (Hernandez, Nowack & Mitrano, 2017). However, the outcomes of available studies vary and need to be reconciled to better understand the different drivers (e.g. regarding the impact of detergent or softeners). Besides laundry conditions, it is important to note that the characteristics of the textile, i.e. fibre, yarn and fabric type, may also affect the fibre release, creating opportunities for improved textile design (Cesa, Turra & Baruque-Ramos, 2017).

Challenges and knowledge gaps

Public concerns about the issue of plastic pollution are apparent and legitimate but poorly understood from a scientific perspective. Public opinion is determined by a range of factors, scientific evidence being just one aspect. Interestingly, the drivers of public risk perception on the issue are, to date, poorly understood. Behavioural research can provide a better understanding, guiding decision-making and providing the basis for generating acceptance of future policies on plastic pollution.

While bringing some benefits, quick fixes are often ineffective and distracting. Recognising that solutions to plastic pollution will need to be implemented incrementally, some of these quick fixes, or 'low-hanging fruit', may be inappropriate because they do not address a relevant proportion of the problem. Because data on the appropriateness and efficiency of these quick fixes is lacking, it is difficult to come to an informed conclusion.

By definition, 'wicked problems' are hard to solve. As explained above, plastic pollution is a 'wicked problem' involving multiple, highly interconnected and interdependent drivers and impacts (Kramm, Volker & Wagner, 2018 and Peters, 2017). Hence, developing solutions is especially challenging as the reasons and impacts of plastic pollution affect each other. The same can be said about potential solutions. Implementing changes to one part of the complex system can have unanticipated impacts on other subsystems. Current solutions rarely take these systemic effects into account.

A risk assessment of plastic pollution is lacking. While taking a precautionary approach to plastic pollution is legitimate, the absence of an evidence-based risk assessment prevents the structuring and prioritisation of solutions, for instance by identifying the most problematic materials and products.

So far, research on plastic pollution has mostly focused on describing the problem rather than contributing to solutions. No doubt it is critically important to close the knowledge gaps in plastic pollution. However, adding more descriptive evidence on the severity of an issue often does not affect public opinion or policymaking. Instead, understanding the processes driving plastic

Table 3: **Possible measures for mitigating plastic pollution at different stages of the plastics life cycle**

<table>
<tr><th></th><th>Design/Production</th><th>Use/Consumption</th><th>Collection/Transfer</th><th>Treatment/Recycling</th><th>Clean-up</th></tr>
<tr><td rowspan="4">Packaging</td><td>Packaging tax</td><td>Plastic bag tax</td><td colspan="3">Deposit-refund scheme for drink containers and packaging</td></tr>
<tr><td>Redesign caps/lids</td><td>Public spots for water refills</td><td colspan="2" rowspan="2">Improvement of wastewater treatment plants to retain microplastics from urban and industrial effluents</td><td rowspan="2">Removal of marine litter in sensitive areas</td></tr>
<tr><td>Eco-tax on specific plastics</td><td>Develop certification schemes</td></tr>
<tr><td colspan="2">Reduce packaging by selling products in bulk and reusing</td><td colspan="2">Sorting of municipal waste and incineration of non-recyclables</td><td>Regular beach clean-up campaigns</td></tr>
<tr><td rowspan="2">Construction</td><td colspan="2">Use of alternative biodegradable building materials</td><td colspan="2" rowspan="2">On-site collection, sorting and valorisation of Construction & Demolition (C&D) waste</td><td rowspan="2">Collection and removal of old or abandoned nets for recycling and incorporation into new products
(e.g. Net-Works)</td></tr>
<tr><td>Apply ‘design for deconstruction’ methods in materials design</td><td>Sustainable use of natural materials for insulation (e.g. seaweed)</td></tr>
<tr><td rowspan="2">Domestic</td><td colspan="3">Awareness campaigns for proper disposal of plastic waste, including labelling (e.g. Bag it, Bin it, UK)</td><td></td><td rowspan="2">Clean-ups at river mouths, voluntary beach clean-up
(e.g. Let’s Clean up Europe)</td></tr>
<tr><td colspan="2"></td><td colspan="2">Sorting of household waste and incineration of non-recyclables</td></tr>
<tr><td rowspan="3">Transport</td><td colspan="5">Strategies for Extended Producer Responsibility (EPR), requiring producers to be responsible for the entire life cycle</td></tr>
<tr><td rowspan="2">Use of organic fillers in automotive plastics (e.g. tomato skins used by Ford)</td><td rowspan="2"></td><td colspan="3">Free take-back services for End-of-Life Vehicles (ELVs)</td></tr>
<tr><td colspan="2">Material Recovery Facilities (MRFs) for materials found in ELVs</td><td></td></tr>
<tr><td rowspan="4">Electrical</td><td colspan="5">Plastic cycle chain voluntary agreement between stakeholders to achieve a circular economy for plastics</td></tr>
<tr><td rowspan="3">Apply ‘easy-to-recycle’ methods in equipment design</td><td rowspan="3">Optimise maintenance services to extend the life expectancy of equipment</td><td colspan="3"></td></tr>
<tr><td colspan="2">Recycling centres for the centralised collection of large devices</td><td rowspan="2">Fishing for Litter programme – collection of litter accidently caught during fishing operations and appropriate sorting and treatment
(e.g. Glasgow, SW England)</td></tr>
<tr><td colspan="2">Community banks for the collection of small electrical devices</td></tr>
<tr><td rowspan="2">Medical</td><td>Resource-efficient production processes</td><td></td><td colspan="2" rowspan="2">On-site sorting of non-hazardous plastics for subsequent waste treatment
(e.g. incineration of disposable gloves)</td><td rowspan="2">Removal of macro-waste before disposal of dredged sediments in the sea</td></tr>
<tr><td colspan="2">Use of pulp-based materials where applicable
(e.g. Vernacare products)</td></tr>
<tr><td rowspan="3">Others</td><td colspan="4">Awareness raising activities about marine litter and potential solutions</td><td></td></tr>
<tr><td colspan="2">Ban of microbeads in personal care products and cosmetics</td><td colspan="3">Zero plastics to landfills (e.g. Germany)</td></tr>
<tr><td>Substitution of synthetic cigarette filters with natural materials</td><td colspan="3">Pay-as-You-Throw: municipal waste charges based on the amount of waste produced</td><td></td></tr>
</table>

KEY: ■ Policy instruments ■ Economic incentives ■ Technological innovation ■ Voluntary initiatives

Source: Sebille, Spathi & Gilbert 2016, adapted from Veiga et al., 2015.

pollution and thus working towards appropriate solutions can be more effective. Currently, there is little research published in that direction.

Current solutions largely focus on the after-use phase of plastics. Performing clean-up operations and improving waste management certainly has a range of benefits. However, considering the principles of the waste hierarchy and circular economy, an emphasis on upstream solutions may promote more effective solutions. Similarly, improved design of yarn and textile to reduce microfibre generation can bring more effective solutions than end-of-pipe filtering methods.

A systematic evaluation of the appropriateness and efficiency of available solutions is lacking. Despite a plethora of solutions having been proposed, their account in the scientific literature remains largely anecdotal. In addition, there are only a few quantitative comparisons of the efficiency of different options. The reason for this is that the knowledge and problem structuring needed to perform such assessments is lacking.

Policy recommendations and R&I priorities

Policy recommendations

Take a systems thinking approach when harmonising and developing policy frameworks related to plastics and pollution. By acknowledging the complexity of plastic pollution, it becomes obvious that the quick fixes promoted or implemented to date are mostly insufficient and/or create (infrastructure) lock-ins. Thus, it is imperative to promote a more systemic approach, which addresses the root causes of the problem and takes a long-term perspective.

Develop a framework to evaluate the appropriateness and effectiveness of available solutions systematically based on systems thinking and in line with circular economy principles. This require promoting the development of common measures (e.g. for marine litter categories and soil pollution) and assessment tools. Take into account the environmental, economic and societal costs and benefits of the solutions and compare these to the costs of inaction.

R&I priorities

Provide financial incentives for R&I that combine an understanding of the key processes of the problem with the development and assessment of solutions. Prioritise research that focuses on understanding the factors driving the impacts of plastic pollution rather than adding more descriptive data. These new insights can be combined with the development of safer materials and processes. In this context, safe-by-design and green chemistry should be priorities in Europe’s innovation agenda.

Provide financial incentives for innovations that tackle the problem at the root, guided by the most recent scientific evidence. Develop mechanisms to feed back the constantly evolving scientific understanding of plastic pollution into the processes of innovation and decision-making. Ensure that the waste hierarchy is the guiding principle for those activities and shift attention to the upstream part of the plastics life cycle to promote effective solutions.

Provide funding to develop and implement a risk management methodology of plastic pollution, following a precautionary approach. Support research that closes the knowledge gaps and develop an adequate risk assessment framework. This will enable a prioritisation of risks in subsystems (e.g. specific habitats) that, in turn, will guide the implementation of appropriate solutions.

Provide funding to understand the drivers of public risk perception of plastic pollution. The human dimension of the issue is poorly understood. Promoting social and behavioural research to uncover the factors influencing public opinion on the downsides of the plastic age will support the development of new solutions and improve societal acceptance of existing solutions.

2 SUBSTANCES OF CONCERN TO HUMAN AND ENVIRONMENTAL HEALTH

Plastics are used in many products for a broad range of applications with possibly as many technical requirements. A plastic item's performance, such as strength, flexibility and aesthetical appearance, is to a large extent determined by its chemical composition, which also influences its chemical safety. In general, most plastics are complex chemical mixtures and contain a range of chemicals, added both intentionally and non-intentionally, such as chemical impurities. Importantly, some of the substances present in plastics, and other materials, are unknown. The intentionally used substances have different functions (i.e. monomers and additives), enabling different properties, and can be categorised as such. National and EU legislation addresses some of these functionality categories with the aim of minimising or eliminating possible negative health impacts, as associated with the migration of substances out of plastics. This chemical migration depends on a substance's properties and concentration, the properties of the polymer matrix, the surrounding media, and the plastic article's production, use and after-use processing. Understanding migration is an important aspect of assessing the types and levels of the chemicals that humans and the environment could become exposed to. In addition to exposure, risk assessments include an evaluation of potential hazards. In this chapter, all functions of plastics and therefore all possible chemical compositions are considered from a qualitative perspective, focusing on toxicity. The chapter also describes how R&I can both improve our understanding of the risks and provide safe alternatives which deliver a similar, or even better, function.

2.1 Risk assessment, impact and regulation related to substances in plastics

State of play

Humans and the environment are exposed to many different types of chemicals, including substances that raise concerns, present in diverse plastic products. In addition to other sources, plastics are a relevant source of potential human exposure to hazardous chemicals (Halden R. U., 2010; Biryol, Nicolas, Wambaugh, Phillips & Isaacs, 2017; United Nations Environment Programme, 2018). In general, during plastics production, some of the substances that have been or still are used intentionally are chemicals raising concerns about their impact on human and environmental health[4] (Geueke, Wagner & Muncke, 2014). Examples include polybrominated diphenyl ethers (PBDEs) used as flame retardants, bisphenol A (BPA) used as a monomer in polycarbonate plastics, ortho-phthalates like diethylhexyl phthalate (DEHP) used as plasticiser in polyvinylchloride (PVC) plastics, cadmium zinc sulphide used as a colourant, lead phosphite used as stabiliser, triclosan or organotins, used as biocides, and metal salts such as antimony trioxide used as a catalyst in polyethylene terephthalate (PET) plastics. Biomonitoring studies demonstrate the presence of plastic additives in humans (Meeker, Sathyanarayana & S., 2009). In addition, at least one study has shown that avoidance of plastic food contact articles, such as packaging or kitchenware, is effective for reducing levels of chemicals of concern in individuals (Rudel et al., 2011). Human exposure to some types of chemicals of concern present in plastics, especially

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[4] *Henceforth abbreviated to substances/chemicals of concern.*

Table 4: EU legal requirement for safety assessment of plastics substances under selected regulations

Plastics substance type	EU 1907/2006 REACH[5]	EU 10/2011 plastic FCMs[6]	EU 282/2008 Recycled plastic FCMs	EU 1272/2008 CLP[7]
Monomers	✓	✓	✓	✓
Polymers	X	✓[8]	✓[9]	✓
Catalysts	✓	✓	✓	✓
Polymerisation agents	✓	X	X	✓
Polymer stabilisers	X[10]	✓	✓	✓
Solvents	✓	X	X	✓
Other additives	✓	✓	✓	✓
Colourants, pigments	✓	X	X	✓
NIAS[11]	X	✓[12]	✓[13]	X

✓ Risk assessment is required   X Risk assessment is not required

during sensitive windows of development like pregnancy, are associated with some noncommunicable diseases, also known as chronic diseases (Talsness, Andrade, Kuriyama, Taylor & vom Saal, 2009; Landrigan et al., 2017 and Chamorro-García et al., 2018).

The chemicals' impacts on health are evaluated using risk assessments, commonly used for single substances. Risk assessment for plastics relies on information about a plastic product's use and its chemical composition. Information is required on the migration (i.e. the transfer of a chemical from the plastic into food, air, water or other environmental media) and exposure levels (humans or the environment), as well as data on a substance's toxicity, i.e. understanding what types of toxicological effects are observed at which levels. In the EU, the Regulation concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) has been adopted to improve the protection of human health and the environment from the risks that can be posed by chemicals, while enhancing the competitiveness of the EU chemicals industry (European Commission, 2006b and ECHA). Specific legislation exists for different applications, and the legal requirements for performing risk assessments differ for distinct uses of chemicals in plastics and different plastic products, based on the regulatory context. Hazardous chemicals may therefore be allowed in products where human exposure can be excluded according to the product's intended use. Different methods exist for ranking the toxicity of chemicals, although there is no comprehensive inventory of all chemicals used for the manufacture of plastics and/or present in different finished plastic articles (Lithner, Larsson & Dave, 2011 and Rossi & Blake, 2014). The Chemicals associated with Plastic Packaging database (CPPdb) provides information on known additives relevant for plastic packaging. It includes their respective hazard data on substances and mixtures related to the EU Regulation on Classification, Labelling and Packaging, if available (Groh et al., 2019 and European Commission, 2008c). Hazard testing is required for intentionally added substances in the production of plastics (see Table 4). Non-intentionally added substances (NIAS) are reaction by-products, impurities or breakdown products and they are present in all finished plastic articles (Figure 7). NIAS in plastics need to be risk assessed if they are present in plastics intended for food contact use, but not for other types of applications. For plastic FCMs, information on substances present after the first manufacturing step of polymerisation is submitted to EFSA for the safety review (European Food Safety Authority CEF Panel, 2017). However, this information, which includes data on NIAS, is not made publicly available. For FCMs in the EU, the requirements for toxicity testing are described in EFSA's FCM Note for Guidance and a list of the permitted monomers and additives for plastic FCMs is maintained according

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[5] *All substances, apart from polymers, need to be registered if more than 1 tonne is produced/imported annually.*

[6] *FCM: food contact materials and articles; compliance with Regulation (EC) No 1935/2004, Article 3 is required.*

[7] *CLP: Regulation on Classification, Labelling and Packaging of substances and mixtures (EC) No 1272/2008.*

[8] *With exceptions, Commission Regulation (EU) No 10/2011, Article 6d.*

[9] *Ibidem.*

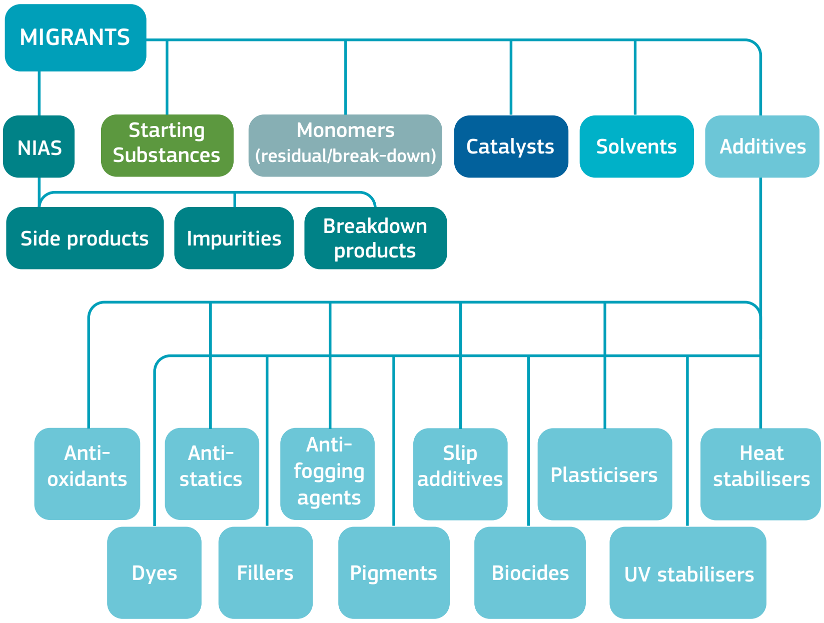
[10] *Additives which are necessary to preserve the stability of a polymer must be regarded as part of the polymer in accordance with Article 3(1) of REACH. In that regard, they do not need a separate registration. If they are manufactured or imported in the EU, in quantities of more than 1 tonne per year, they need to be registered under REACH.*

[11] *NIAS: non-intentionally added substances; reaction by-products, breakdown products, impurities including oligomers.*

[12] *EU 10/2011, Article 19 requires these substances "shall be assessed in accordance with internationally recognised scientific principles on risk assessment".*

[13] *Ibidem.*

Figure 7: Types of chemicals that can migrate from finished plastics articles



Source: Muncke J., 2009

to the provisions of Commission Regulation (EU) No 10/2011 (European Food Safety Authority, 2008b). The toxicology testing is triggered by the exposure level and not by the classification of the substance. In addition, various NIAS may be present in used plastics and consequently can be an issue for recycled plastics. For recycled plastics intended to come into contact with food, recycling processes must be authorised by the European Commission based on an EFSA scientific opinion, according to Commission Regulation (EC) No 282/2008. Part of the scientific opinion evaluates the decontamination efficiency of the recycling process (European Food Safety Authority, 2008a).

EU chemicals law identifies substances of very high concern through REACH, with polymers exempted from registration. In general, all substances imported or produced in quantities of more than 1 tonne per year must be registered with ECHA under REACH (European Commission, 2006b). Substances may be identified as Substances of Very High Concern (SVHCs) under REACH if they are carcinogenic, mutagenic or toxic to reproduction (CMR); persistent, bioaccumulative and toxic (PBT); very persistent and very bioaccumulative (vPvB), or if they are of an equivalent level of concern (e.g. endocrine disrupting chemicals (EDCs)). Substances on the Candidate List of SVHCs can be used in the manufacture of plastics, but there is a requirement for producers to provide information for consumers and other stakeholders on their presence in finished articles and in waste (for weight levels above 0.1 %, equal to 1 000 mg/kg). SVHCs may be included in the REACH Authorisation List (Annex XIV), in which case they must be authorised prior to use, if they are used in the EU. DEHP, used as a plasticiser, is an example of a chemical now subject to authorisation under REACH. Polymers are exempted from registration and evaluation under REACH as polymers are assumed to be of low concern due to their high molecular weight (some exemptions apply). However, they can be subject to restriction or authorisation.

Certain chemical uses are subject to regulations which are separate from REACH. For example, biocides can be present in plastics but are regulated according to the Biocidal Products Regulation (EU) No 528/2012. Separate product legislation also exists for toys, electrical and electronic equipment (RoHS; Restriction of Hazardous Substances Directive 2002/95/EC) and food contact materials ((EC) No 1953/2004 and (EU) No 10/2011). Chemicals intentionally used in the manufacture of plastic food contact materials and articles are exempt from REACH for human health effects ((EC) No 1907/2006, Article 14.5.a). The Regulation on Classification, Labelling and Packaging of substances and mixtures ((EC) No 1272/2008) applies to all chemicals imported or manufactured in the EU, including polymers. In principle, waste is not addressed in REACH as substances resulting from recovery processes are exempted from registration under REACH, if they are the same as already registered by the registrant (Stenmarck Å. et al., 2017). The RoHS Directive lists select hazardous substances with limits for electrical and electronic equipment put on the market in the EU, which apply to both domestic and imported production.

Different chemicals in plastic products are subject to different toxicological assessments with different levels of assessment. Toxicity testing requirements under REACH and other EU regulations (e.g. for plastic food contact materials) are tiered according to production volume or human exposure levels, meaning that toxicological data requirements increase if production levels (e.g. in REACH) or migration levels (e.g. for FCMs) increase. Current regulatory toxicity testing and assessment approaches focus on toxicological assessments based on cell-based (*in vitro*) assays, for lower tier and lower estimated exposure, and on whole animal testing (*in vivo*) conducted in accordance with standardised test guidelines or protocols (e.g. Organisation for Economic Cooperation and Development tests). Currently, there is a shift away from whole-animal testing to in vitro and computational methods (*in silico*), where tools are being designed for a comprehensive mechanistic understanding of the cause-consequence relationships of adverse chemical effects (H2020 EU-TOXRISK). Reasons for this shift are ethical issues related to the use of animals in toxicological experiments, as well as the higher costs and longer lead time of *in vivo* testing. REACH also promotes alternative methods for the hazard assessment of substances in order to reduce the number of tests on animals (ECHA). From a more general perspective, legislative activities are ongoing to streamline the interface between chemical, product and waste legislation (European Commission, 2018n).

The release of harmful substances has been estimated to have a sizeable impact on human health and the environment in Europe and worldwide (Bernhardt, Rosi & Gessner, 2017 and FP7 RISKCYCLE). Exposure to hazardous chemicals stemming from a wide range of industries has been estimated to contribute substantially to disease and dysfunction across the lifespan, amounting to costs of hundreds of billions of euros, e.g. for endocrine and neurodevelopment toxicities (Altenburger et al., 2018)[14]. For example, it has been estimated that the costs of medical care attributable to obesity in the United States exceeds USD 200 billion a year (Lind, Lind, Lejonklou, Dunder & Guerrero-Bosagna, 2016). An estimated 1.3 million lives and 43 million disability-adjusted life-years (DALYs), a measure of disease burden, were lost in 2012 due to exposure to selected chemicals, including sources other than plastics (World Health Organization, 2016). Environmental chemical exposure, including from plastics, incurs costs that may exceed 10 % of the global domestic product and current DALY calculations may substantially underestimate the economic costs associated with preventable environmental risk factors (Grandjean & Bellanger, 2017). Several plastic monomers, additives and known NIAS are endocrine disrupting chemicals that interfere with the hormone system (United Nations Environment Programme, 2017). Some EDCs, for example, have been associated with adult obesity if foetuses were exposed via their mothers, making both the dose and the timing of an exposure relevant for toxicity outcomes, i.e. the developmental origins of adult disease hypothesis (DOHAD) (Lind, Lind, Lejonklou, Dunder & Guerrero-Bosagna, 2016). An additional challenge related to EDCs is the phenomenon of the non-monotonic dose response, which reduces the scientific certainty of safety thresholds derived by extrapolating high-dose toxicological test results to lower levels relevant to human exposure (Vandenberg et al., 2012; Lanphear, 2017 and Solecki et al., 2016). According to a 2016 report commissioned by EFSA, taking into account the type (hormones and pharmaceuticals were excluded) and amount of data selected and analysed, the non-monotonic dose response as a common phenomenon is not supported for substances in the area of food safety (Beausoleil et al., 2016). While the evidence for such a non-monotonic dose response as a common phenomenon is presently limited, it cannot be ruled out as such and further work is needed. Furthermore, some chemicals in plastics may modify the epigenome and lead to transgenerational health effects which manifest themselves several generations after chemical exposure has occurred (Manikkam, Tracey, Guerrero-Bosagna & Skinner, 2013 and H2020 EUROMIX).

Impacts of plastic articles could in theory be further assessed using a full life-cycle analysis. This would include all emissions and extractions involved in the production and supply chain, related to, for example energy, auxiliary materials, waste treatment, and capital goods. However, production data are only available for very few plastic additives, and data regarding use and waste treatment of additives are generally absent (FP7 RISKCYCLE). Human health impacts are usually studied with regard to production and after-use impacts, with human body burdens of few chemicals used in plastics manufacture having been described (Koch & Calafat, 2009).

Closing the material loop, for example through mechanical recycling, can lead to the presence of chemicals of concern in new products. The recycling of plastics is challenging, as chemicals of concern can be introduced, or they may be present in waste originating from products with a previous different intentional use (for example, brominated flame retardants) (Leslie, Leonards, Brandsma, de Boer & Jonkers, 2016). In general, companies are responsible for the safe use of a chemical substance throughout the life cycle. However, while this is required by REACH, compliance with the obligation to notify ECHA about the presence of substances on the Candidate List of SVHCs, and to register substances that are imported or produced in quantities of a least 1 tonne per year is low (German Federal Institute for Risk Assessment (BfR), 2018). In addition, information shared in the supply chain or with ECHA is often not available for the final article. There are exceptions, such as the notification requirement for substances on the Candidate List which are present in articles above a concentration of 0.1 % weight by weight and which are imported or produced in quantities totalling over 1 tonne per year. Therefore, while the latest revision of the Waste Framework Directive aims to strengthen and widen the availability of such information for Candidate List substances, it is currently not accessible to companies handling or recycling waste (European Commission, 2018h). The EU-wide certification programme EUCertPlast for used plastics recyclers was developed under the European Commission's Eco-Innovation Programme. It standardises plastics recycling and addresses pertinent issues such as traceability, conformity assessment, and recycled content (Stenmarck Å. et al., 2017). The Stockholm Convention on persistent organic pollutants influences plastics recycling, because all waste containing POPs above substance-specific limit values should be destroyed. Further, the use of POPs in new products is prohibited. The Restriction of Hazardous Substances Directive 2002/95/EC limits levels of specific chemicals of concern in Waste Electrical and Electronic Equipment (WEEE) products, an issue especially linked to occupational exposure in informal recycling (see also Chapter 6). Guidance for Best Available Techniques (BAT) and Best Environmental Practices (BEP) for plastics recycling has been developed by UN Environment. For plastic food contact materials and articles, the EFSA reviews recycling processes and publishes Scientific Opinions, as required under Regulation (EU) No 282/2008 on recycing plastics for food contact uses. The EU Commission can authorise specific recycling processes, but has not done so to date (26 November 2018).

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[14] *This position paper has been signed by coordinators and representatives of several EU-funded research projects: H2020 EDC-MIXRISK, H2020 EUROMIX, H2020 EU-TOXRISK, H2020 HBM4EU, and FP7 SOLUTIONS.*

Challenges and knowledge gaps

Large knowledge gaps persist regarding the presence of hazardous chemicals in plastics. Plastics contain many data-poor or even unknown substances (Onghena et al., 2015; Wagner, Schlüsener, Ternes & Oehlmann, 2013 and Groh, et al., 2019). Hence, one of the drawbacks of computational tools for assessing hazardous chemicals in finished plastic articles is that they only identify the already known hazardous substances or known hazard properties associated with chemical structures. Intentionally added substances in plastics can be assessed for their risk using both exposure and toxicity data. However, several challenges exist, such as the availability of data or its quality and suitability for risk assessment (Marovac, 2017 and H2020 EUROMIX).

Mixture toxicity, aggregate exposures, unknown substances in plastics and endocrine disruption are not addressed by current risk assessment approaches. Toxicity may be affected by mixtures of chemicals migrating at the same time from a finished plastic article. Humans are usually exposed low levels of chemicals migrating from plastics. However, chemical mixtures can cause adverse effects even when the single substances present in the mixture would not lead to an effect at their individual levels (H2020 EUROMIX). Human biomonitoring studies have shown that Europeans have a considerable number of man-made chemicals in their bodies, and the environment too is exposed to mixtures of many different chemicals, including those leaching from plastics (Altenburger et al., 2018 and Rochman C. M., 2015). However, the risk of chemical substances is usually assessed based on the specific uses and applications. Therefore, it mostly addresses the exposure to single substances through one application only, while it is likely that the same chemical is used in different products, i.e. aggregate exposure (Joint Research Centre, European Commission, 2018). In some cases, aggregate exposure has been taken into account for setting the migration limit, including for aluminium, some acrylates and zinc salts. Furthermore, as NIAS can migrate from plastics, they are relevant for human and/or environmental exposure. However, many of them are unknown while others lack toxicity data, which makes it a challenge to assess their risk using conventional approaches. In the case of plastic FCMs, substances are risk assessed by the EFSA, as required by the legislation (European Food Safety Authority CEF Panel, 2008 and European Food Safety Authority CEF Panel, 2016).

Regulations and their implementation fail to adequately address the assessment of NIAS present in finished articles. In general, plastics are not assessed as finished articles. While reporting obligations exist for Candidate List substances and legal requirements regarding finished articles are in place for FCM items and toys, there is low compliance from industry and insufficient guidance on the methodology to be used, limited enforcement and no obligation regarding mixture toxicity (European Commission, 2011a; European Commission, 2009b and Muncke et al., 2017). In particular, identification of NIAS, including oligomers, in finished plastic articles is challenging and not always possible (Onghena et al., 2016; Hoppe, de Voogt & Franz, 2016 and Onghena et al., 2015), although it is legally required for plastic food contact materials and articles. In such cases, NIAS in finished articles may remain unknown (Bradley & Coulier, 2007; Hoppe, de Voogt & Franz, 2016 and Vera, Canellas & Nerín, 2018). The levels of unknown chemicals present in plastics cannot be assessed, but concentrations can be estimated with some uncertainty using semi-quantitative, non-targeted analytical chemistry approaches (Pieke, 2017). Alternatively, novel approaches can be applied where biological effect detection is combined with analytical chemistry (Bio-based Industry Consortium, 2017 and Onghena et al., 2015). Enforcement of the legal requirement to assess NIAS has shown to be highly challenging, with little response from plastic resin manufacturers and insufficient information provided to authorities, as a campaign in Switzerland in 2014 showed (McCombie, 2016 and Food Packaging Forum, 2015). So far, the European Commission has not issued guidance for assessing NIAS, including any unknown compounds, in plastic food contact materials and articles.

While they are promising approaches, *in silico* and *in vitro* tools for hazard assessment are currently associated with large scientific uncertainty. Biological systems do not easily lend themselves to simplification using approaches based on linear, mechanistic, i.e. cause-effect correlation, because they are highly complex with many different feedback loops (Soto & Sonnenschein, 2018). As *in silico* and *in vitro* approaches aim to simplify biological processes, they do not address all possible biological interactions, thus increasing scientific uncertainty. However, their use for prioritising chemical testing needs is to be encouraged as it is likely that further development of these approaches will result in more robust tools (Van Bossuyt, Van Hoek, Vanhaecke, Rogiers & Mertens, 2017 and European Commission, 2017a). The study of biological organisation is a prerequisite for understanding how chemicals can cause disease. Considering an organism in its entirety is a prerequisite for successfully reducing the scientific uncertainty inherent in *in vitro* and *in silico* toxicological data (Soto & Sonnenschein, 2018). Despite limited progress in understanding complex diseases, there is an assumption that explanatory molecular mechanisms will be found to explain biological phenomena.

Current life-cycle assessments do not capture all the relevant impacts of plastic toxicity along the value chain (Camboni, 2017). The environmental impact of plastics is often quantified using life-cycle assessment (LCA) or assessed from a product environmental footprint perspective (European Commission). While some tools are being developed to calculate the risk of exposure to chemicals in a broader sense, such as ProScale and ECETOC's Targeted Risk Assessment tool, additives in plastic products are often not included in LCAs (ProScale and ECETOC). This is mostly because data on the use of additives in specific plastic products and their related life-cycle inventory data are often not available (FP7 RISKCYCLE). In particular, data on the types of additives used in products, production data of additives and emission data of additives from plastics in the use and waste phase are lacking (FP7 RISKCYCLE). As such, current LCA methodologies are not suitable, or simply not designed, for predicting the actual toxic impacts of substances migrating from a plastic article, and risk assessment (RA) is the method of choice for this purpose. However, LCA considers life stages other than just the intended use phase, and therefore might include side effects that are absent from RA but important for comparing products (FP7 RISKCYCLE and USEtox). Furthermore, pertinent knowledge gaps, such as the absence of information on a product's chemical composition, are not penalised in LCA, and the chemical safety of the finished plastic article, i.e. assessing mixture toxicity, is generally not within the scope (Ernstoff, Fantke, Huang & Jolliet, 2017). As a consequence, data-rich materials can be scored less favourably compared to materials like plastics which have many information gaps.

The potential presence of hazardous substances in recycled plastics, and lack of knowledge thereof, creates challenges. In general, recyclers struggle to guarantee the exact content of secondary material, which limits recycling (Stenmarck Å. et al., 2017). Global flows of recycling products are scarce and difficult to investigate (FP7 RISKCYCLE). The need for knowledge of substances included in plastics manufactured from recycled material is challenging for the recycler, since the composition of the waste may be unknown and detailed chemical analysis is not always possible (Stenmarck Å. et al., 2017). Materials need to be traceable throughout the life cycle of a product. There is a risk that hazardous substances are spread to clean-material flows during collection, sorting and recycling. For example, due to the illicit recycling of plastic from WEEE into food contact articles, hazardous brominated flame retardants have been found in FCMs on the European market, which are not authorised for food contact (Stenmarck Å. et al., 2017; Turner, 2018 and Samsonek & Puype, 2013). Several other chemicals of concern are associated with recycled plastics for food contact uses (Turner, 2018 and Geueke, Groh & Muncke, 2018). Additives can also be released from plastics during the various recycling and recovery processes, and from the products made from recycled material (Hahladakis, Velis, Weber, Iacovidou & Purnell, 2017). Occupational exposure to hazardous substances in plastics during collecting and sorting is another issue requiring increased attention (see Chapter 6).

Intentional biodegradation of plastics may lead to chemical pollution. Plastics degrading under environmental conditions may also be a source of hazardous chemicals entering the environment (Shah, Hasan, Hameed & Ahmed, 2008). While soil quality may be affected when biodegradable plastics decompose, demonstrating the absence of ecotoxicological impacts from biodegradable plastics is not always a requirement (Bettas Ardisson, Tosin, Barbale & Degli-Innocenti, 2014). See Chapter 9 for more on this topic.

The regulatory requirements for substances in plastics vary across product categories and thus regulatory frameworks. They depend on a range of factors, including the type of chemical and its function, e.g. as a plasticiser or monomer (see Table 4), its use, i.e. the product category, and after-use reprocessing, e.g. recycling. Substances intentionally used to manufacture plastics for different applications are required to be assessed for their safety according to different European legal frameworks (Table 4). Regulatory limits for acceptable migration of certain chemicals from plastic products can be defined, for example for plastic FCMs.

Some substances in plastics have no legal requirement for assessment of their chemical hazard or risk. These substances include polymers and polymer stabilisers that are not intended for food contact, and must be regarded as a part of the polymer if necessary to preserve the stability of a polymer. Oligomers, which are generally described as polymers with a molecular weight lower than 1 000 daltons, form a special case, and there is no consensus on whether they are NIAS. Safety assessments for oligomers are not required under REACH (Hoppe, de Voogt & Franz, 2016 and Groh, Geueke & Muncke, 2017).

Hazardous chemicals in plastics that are restricted under certain legal frameworks are authorised in other legal frameworks. Some SVHCs which have been identified as being hazardous under REACH are authorised for use in food contact plastics with specific migration limits (SMLs), despite evidence of migration and hence likely human or environmental exposure (Geueke & Muncke, 2017). One example is the plasticiser benzyl butyl phthalate (BBP), which is scheduled for phase-out under REACH yet authorised for use in plastic FCMs. At the time of writing, the safety of BBP is being re-evaluated by EFSA at the request of the European Commission (European Food Safety Authority CEF Panel, 2018).

Hazardous chemicals may be present in imported products due to gaps in regulation or insufficient enforcement. The obligation to notify ECHA about the presence of Candidate List substances in articles above 0.1 % weight by weight and to communicate this notification down the supply chain applies to all articles, both imported and EU-made. However, obligations to report information on the full chemical composition do not apply to imported finished articles, with the exception of plastic food contact materials and toys (European Commission, 2011a and European Commission, 2009b). Even with FCMs and toys, as explained above, there is insufficient guidance on the methodology to be used, limited enforcement and no obligation regarding mixture toxicity. Lack of specifications for the chemical composition of traded goods leads to potentially unsafe consumer and industrial goods being imported into the EU, and to competitive disadvantages for European manufacturers (FP7 RISKCYCLE). Further, while restrictions can be imposed under REACH on (almost) any substance, the exemption of authorisation requirements for imported articles creates a competitive disadvantage for European manufacturers of articles (European Bioplastics, 2016a and European Commission, 2006b). Resources dedicated to the enforcement of chemical policy are in general inadequate (McCombie, 2016).

Limits for some chemicals authorised for use in plastics cannot be enforced. Levels of chemicals migrating from finished plastic articles cannot be measured when no chemical standards are available for calibration of chemical analysis equipment. Indeed, for roughly half of the over 900 substances authorised for use in plastic food contact materials and articles no standards are publicly available, meaning that regulatory limits cannot be enforced for almost half of the authorised compounds (Joint Research Centre, European Commission, 2015).

Chemicals or levels of chemicals considered safe today may be known to be unsafe in the (near) future. With evolving scientific understanding, chemical safety considerations are changing over time. The issue of legacy compounds challenges the principle that information in the supply chain must only be supplied for known hazardous substances and above certain levels. It also hampers the safe reuse and recycling of materials with a long service life, such as used in the construction sector (e.g. flooring and window frames). For example, perfluorinated substances have been widely applied in products since the 1960s but their use only started being restricted 10 years ago, as publicly available information on their hazards emerged gradually over time (Grandjean P., 2018).

Policy recommendations and R&I priorities

Policy recommendations

Enforce existing European chemical regulations, such as those relating to REACH, FCMs and toys. Ensuring the chemical safety of products placed on the European market requires a market-relevant incentive for adhering to regulatory limits, e.g. for substances on the Candidate List of SVHCs. This can be achieved by enhanced enforcement of product testing by authorities or government-supported third parties (such as independent testing labs). The relatively high, possible additional costs for start-ups and small and medium-sized enterprises (SMEs) could be balanced by targeted support. Consumer organisations may also play a role in highlighting pertinent issues to the authorities identified from campaigns, to inform a scientifically rigorous analysis.

Extend regulatory requirements based on specific and overall migration from finished products to expand existing measures such as FCM legislation. An assessment of actual mixture exposures in the human population and in ecosystems is a cornerstone of any risk assessment (Altenburger et al., 2018). Effect-based regulatory values (i.e. results from in vitro testing) for mixtures with similar effects need to be developed (Altenburger et al., 2018). A more extensive assessment is also required, as the exposure to 'mixtures' could be either from the same chemicals through multiple routes ('aggregate') or multiple chemicals through a single route or multiple routes ('cumulative') (H2020 EUROMIX). Such considerations have been made for some substances, e.g. for migration of BPA from food contact materials, with other non-food contact exposure routes (thermal paper) being taken into account when setting a legal limit.

Integrate regulatory requirements for plastics additives with endocrine disrupting properties into existing legislation, including those relating to REACH, FCMs and toys. Potency has been deemed irrelevant for the identification of endocrine disrupters, as the same chemical can have very large effect ranges in different biological systems (Bourguignon et al., 2016). To ensure acceptable safety for humans and the environment, and ensure prevention of adverse effects resulting from exposure to EDCs, chemicals used in plastics should be tested for endocrine disrupting properties in the relevant pieces of legislation. However, endocrine activity on its own should not trigger a chemical's identification as an EDC in the regulatory context. It should rely on weight-of-evidence evaluations of both adversity and mode of action together. Adversity implies effects or prediction of effects in intact organisms (Solecki et al., 2016). Adverse effects from combined exposure to relevant different chemicals should be considered in an appropriate risk assessment of chemical substances to ensure human and environmental health (Solecki et al., 2016). The regulations for all types of plastic products should address this issue. The special properties of EDCs also require novel approaches for the assessment of occupational exposure and related risks in the plastics manufacturing industry (Fucic et al., 2018).

Set regulatory requirements for biodegradable plastics to ensure chemical safety for different environments. Plastic articles which are designed with the intention that they degrade in the environment or in (industrial) composting facilities (e.g. mulching films, single-use takeaway food containers and tea bags) should fulfil criteria on ecotoxicity for all chemical components of the finished plastic article, in addition to meeting standards on mineralisation. In addition, products which are designed in such a way that their degradation leads to improved compost or soil quality should be preferred.

Harmonise different chemical policies by using positive and negative lists of chemicals covering all plastic applications in scope. Synergies between chemical policies should be improved. For example, regulations for plastic toys are stricter compared to requirements under REACH. As a result, recycled material must comply with these regulations, which makes use of recycled plastics, e.g. in toys, less straightforward (Stenmarck Å. et al., 2017). Product designers need to be aware of SVHCs and other hazardous chemicals that can be present in recycled materials if these are used as raw materials. That is why a negative list for the manufacture of plastics, i.e. a list containing all substances which are not permitted in plastics, can be useful, although such a list may be difficult to realise. In addition, a positive list of all chemicals authorised for use in plastics would allow for a qualitative safety assessment and assist with ensuring performance properties, i.e. some chemicals may be known to interfere with function in recycled materials. The monomers and additives in plastic FCMs are regulated under Regulation (EU) No 10/2011, which includes a positive list with legal limits (European Commission, 2011a). Under Regulation (EC) No 282/2008, recycling of plastic FCMs is only allowed for plastics which comply with Regulation (EU) No 10/2011 and therefore the intended use of unauthorised additives can be excluded in this case (European Commission, 2008a).

Develop and implement risk-based management of chemicals that includes chemical migration from plastic products throughout the entire life cycle. Impact assessment methods (such as LCAs to assess the product environmental footprint) should be expanded to take into account chemical migration and toxicity during the use and after-use phase, and relevant industries should provide data on additives in plastics (FP7 RISKCYCLE). This crucial information will also enable estimates of DALYs (Grandjean & Bellanger, 2017). Some tools are already being developed to provide toxicological information on the chemicals used (ProScale, n.d.). Both LCA and chemical risk assessment should play a role in the definition and development of risk-based management of additives (FP7 RISKCYCLE). A novel approach integrates the chemical migration in LCAs of FCMs with the aim of providing an improved and more holistic comparison of different products and functions (Ernstoff et al., 2018). Similar approaches could be taken for other types of plastic products, for example medical devices (Latini, Ferri & Chiellini, 2010).

Provide information and business support to reduce exposure to hazardous chemicals. Public health efforts should focus on the importance of disease prevention by means of reducing avoidable chemical exposure, in addition to efforts for treating disease (Grandjean & Bellanger, 2017). This can be achieved, for example, by educating healthcare professionals on the effects of environmental contaminants on health (Lind, Lind, Lejonklou, Dunder & Guerrero-Bosagna, 2016). Appropriate measures will also require the compilation of necessary information, such as the intentional use and/or presence of chemicals of concern in plastic articles with direct human exposure relevance, such as food contact materials, pharmaceuticals or cosmetics packaging. In addition, measures addressing environmental exposure to chemicals could be linked with thresholds defined under the planetary boundaries concept (MacLeod et al., 2014). Chemicals of concern thereby include substances with CMR properties, persistent and allergenic compounds, as well as immunotoxic, neurotoxic and endocrine disrupting substances.

Provide business guidance on the safety assessment of (unidentified) non-intentionally added substances in plastic FCMs and articles. The legal requirement to assess the safety of all NIAS in plastic FCMs and articles can only be met if clear, realistic and scientifically sound approaches for this purpose are provided by the Commission. Stakeholder input from industry, academia, Member States enforcement labs and public interest groups during the drafting of this guidance is essential.

Provide business guidance on the safety assessment of used and recycled plastics. The revised Waste Framework Directive (EU) 2018/851 specifies that by 2030, 55 % of municipal plastic waste must be recycled. Achieving this goal should not compromise the chemical safety of plastic products, and therefore clear and scientifically informed guidance should be provided on how the chemical safety of plastic waste intended for recycling can be ensured. One approach could be to require the labelling of product content which stays on the product throughout its life cycle (including recycling) (Stenmarck Å. et al., 2017). Furthermore, chemical safety criteria for virgin and recycled materials should be identical for the same intended applications (Stenmarck Å. et al., 2017).

R&I priorities

Provide financial incentives for innovation in designing, producing, using and reprocessing plastics that eliminates or minimises dispersion of hazardous chemicals into the environment. Some plastic products contain known hazardous substances. Dealing with plastic waste in a circular economy should favour solutions where known hazardous substances are contained and not dispersed into the environment. Mixing of plastics containing hazardous substances with non-contaminated material streams during recycling poses a risk and should be avoided.

Provide funding to better understand EDCs and their impact. This should address the existing gaps in knowledge of the scale of the effect of EDCs, especially when combined with exposure to other hazardous substances.

2.2 Substituting substances of concern

State of play

Legislative requirements are considered the main driver of substitution. In particular, identification as an SVHC seems the first key step in initiating the search for safer alternatives, according to a study on chemical substitution carried out within the strategy for a non-toxic environment of the 7th Environment Action Programme (Marovac, 2017). Economic considerations, corporate social responsibility, internal chemical management policies, supply chain requests and consumers' and workers' concerns are also important factors (Marovac, 2017). However, practical examples of successful substitutions are limited. One case of a successful substitution, driven by the Stockholm Convention on persistent organic pollutants, are reformulated airliner seat cushions. In an EU-funded research project, halogenated flame retardants that are POPs were replaced by polyurethane foam without expandable graphite, making it suitable for recycling and a more economical alternative compared to materials using non-halogenated flame retardants (FP7 FIBIOSEAT).

Design innovation is important, as the positive impact of substituting hazardous substances in new (plastic) products is likely to be larger than removing legacy elements in recycled materials. This is explained by the fact that intentionally added hazardous chemicals are expected to lead to a greater risk to human health and the environment, compared to the risk arising from recycled plastics materials containing legacy chemicals of concern (Stenmarck Å. et al., 2017). Indeed, mechanical recycling currently requires addition of virgin material and will therefore lead to a dilution of chemicals of concern over time. Also, chemical recycling of plastics is expected to remove chemicals of concern, but this assumption will require verification in large operating plants (see Chapter 8). Notably, if the sole focus were to be the removal of hazardous substances, the mechanical recycling of plastics would be limited, and material flow separation based on the origin of plastic waste would be a critical aspect. For example, the efficient sorting of plastic waste from electrical and electronic equipment containing brominated flame retardants is possible (Stenmarck Å. et al., 2017).

In addition to existing frameworks, new digital technologies are supporting the search for and use of safer alternatives. Several frameworks already exist for substituting hazardous chemicals with better alternatives, including the US EPA alternatives assessment, the Lowell Center reports and the SUBSPORT methodology for alternatives assessment. Innovative *in silico* approaches can be useful for developing less hazardous products, and additional higher-tier testing, such as *in vitro* and *in vivo*, can reduce scientific uncertainty (Cohen, Rice & Lewandowski, 2018; Clean Production Action, 2018 and Schug et al., 2013). A handy resource for identifying alternatives is the online tool Marketplace, which is maintained by a non-profit organisation dedicated to the identification and substitution of SVHCs (ChemSec, 2018). GreenScreen® for Safer Chemicals is a method for chemical hazard assessment designed to identify chemicals of high concern and safer alternatives, which was developed by the US NGO Clean Production Action (GreenScreen). Since January 2018, GreenScreen v1.4 has provided a method for addressing polymers separately. A related but simpler method, the GreenScreen List Translator™, provides a 'list of lists' approach to quickly identify chemicals of high concern. It does this by scoring chemicals based on information from over 40 hazard lists (GreenScreen List Translator). Several other tools and activities of relevance to plastics and chemical safety are available from Clean Production Action, including the Plastics Scorecard and the Chemical Footprint project for measuring and disclosing data on business progress towards safer chemicals (Chemical Footprint Project). Integrated Approaches to Testing and Assessment are pragmatic, science-based approaches for chemical hazard characterisation that rely on an integrated analysis of existing information coupled with the generation of new information using testing strategies. Several different types of data can be combined, e.g. from *in silico*, *in vitro* and *in vivo*. New approaches using *in silico* or *in vitro* data are encouraged to enable increased chemicals assessments without the need for increased resources (OECD). The OECD is also developing so-called Defined Approaches, where the influence of expert judgement is minimised in the use of *in silico* and *in vitro* approaches for chemical safety assessments.

Challenges and knowledge gaps

Barriers preventing successful implementation of safer alternatives include insufficient understanding of technical performance, incumbent technologies and switching costs and risks. The lack of information on the technical feasibility of developing alternatives able to satisfy the customer performance specifications are important obstacles to substitution. Existing technologies typically already meet these specifications, and are integrated into the supply chain. Information on alternatives for substituting harmful chemicals is scarce, and comprehensive legal frameworks to assist with substitution are not available. Public authorities indicated that a major obstacle to supporting and enforcing substitution initiatives is the lack of resources and expertise. Insufficient time to identify and develop suitable alternatives, the excessive increase in the time to market for products containing alternatives and, more generally, the high administrative burden, in particular for SMEs, are noted as reasons for the reluctance to embrace alternatives. Further, there are costs and risks related to switching to alternatives, in particular for cases with specific performance requirements. The available tools for the assessment of alternatives typically combine hazard and risk assessments with economic and technical feasibility, focusing on chemical-by-chemical substitution (Marovac, 2017).

The lack of knowledge of the chemical composition of plastic articles and the related potential negative impact prevents a thorough understanding of the innovation challenges. Some hazardous substances have been shown to migrate from FCMs (Geueke & Muncke, 2017). In general, given the existing legislation, levels of SVHCs in plastic food packaging are likely to be lower compared to other plastic product categories. However, knowledge gaps concerning the exact chemical composition, human exposure and environmental fate remain and need to be acknowledged and addressed (Muncke et al., 2017 and Groh et al., 2019). As such, there is no clear direction or incentive for innovation.

The lack of a systemic approach when innovating for alternatives for chemicals of concern in plastics can lead to regrettable substitutions. For example, the EDC BPA has been banned for use in plastic baby bottles since 2011 but has subsequently been substituted with bisphenol S (BPS), which has similar toxicity properties. The practice of adopting structurally similar alternatives (incremental rather than fundamental substitution) often leads to cases of regrettable substitution. The tools available for the assessment of alternatives typically combine hazard and risk assessments with economic and technical feasibility, focusing on chemical-by-chemical substitution, which is not effective or even feasible for some groups of chemicals. Innovation towards safer alternatives is insufficiently focused on function in the broad sense, including for example, different business models or products.

The current assessment of the finished plastic article's overall migrate and toxicity is insufficient to ensure the chemical safety of the entire product. With advanced understanding of mixture toxicity, a single substance approach is insufficient to assess the safety of plastics where many substances are known to migrate simultaneously. In addition, such an overall assessment is also useful for the identification of compounds driving overall toxicity, and their subsequent replacement with better, less toxic alternatives. For example, in some studies the overall migrate of some plastic bottles and other types of plastic food packaging has been shown to be oestrogenic, i.e. affecting oestrogen hormone signalling in cell-based assays and invertebrate animals (Yang, Yaniger, Jordan, Klein & Bittner, 2011; Wagner & Oehlmann, 2009 and Mansilha, et al., 2013). While it is challenging to identify exactly which substances are responsible for the observed biological effect, this observation highlights the need for further research to improve the overall chemical safety of finished plastic articles, especially those intended for food contact use (Wagner, Schlüsener, Ternes & Oehlmann, 2013).

For some substitutes already in use, little research has been conducted on the potential environmental health implications. For example, nanofillers can lead to chemicals of concern being generated, especially in the case of thermal decomposition or incineration. In particular, incineration of thermoplastics with nanofillers will generate significant levels of high-weight polyaromatic hydrocarbons (PAHs), which are considered more toxic than low-weight PAHs. These substances are assumed to be formed on the released nanoparticulate matter during thermal decomposition (European Commission, 2018l).

Policy recommendations and R&I priorities

Policy recommendations

Continue developing regulations, including REACH, to phase out particularly hazardous substances for all product categories. A clear regulatory framework will drive substitution with safer alternatives. During the transition period, plastics of different origin should be separated in order not to contaminate cleaner plastic material flows with chemicals of concern, and thus ensure the possibility of high recycling rates (Stenmarck Å. et al., 2017). Such regulatory requirements should be enforced for products made in Europe as well as for imports.

Set regulatory requirements for gathering and sharing information on additives and other chemicals used in plastic articles throughout a product's life cycle and among different stakeholders. Plastics additives need to be taken seriously as a part of the life cycle (FP7 RISKCYCLE). For example, an inventory of plastics additives with detailed information on their use and harmonised toxicity data could be established (Groh et al., 2019). In addition to ongoing actions by policymakers, industry needs to play an important role in this data compilation process (FP7 RISKCYCLE and (ECHA, 2018c)). See also Section 5.3 for more information on information flow and transparency throughout the supply chain, topics on which ECHA is currently working (ECHA, 2018a and ECHA, 2018c).

Regulate related chemicals in groups to avoid regrettable substitutions. Regulations on hazardous chemicals should expand their scope beyond one substance at a time to avoid one hazardous chemical being replaced by very similar chemicals that may be equally harmful. For example, substitutes for BPA include BPS, which is suspected to have many of the same adverse health effects as BPA (ECHA, 2015). In the absence of research data showing a related chemical does not have properties of concern, chemicals with a similar chemical structure should be assumed to have similar toxicological properties. This would be supported by risk assessments for groups of chemicals, rather than specific chemicals, in particular for substances which may lead to serious and irreversible effects on human health or the environment, including EDCs, carcinogens, mutagens, PBT/vPvB chemicals, neurodevelopmental and immunotoxic substances. The Commission's 'fitness checks' on the most relevant chemicals legislation (excluding REACH) could be an opportunity to expand the use of more generic risk assessments.

R&I priorities

Provide funding to develop a framework for the identification of suitable safe-by-design alternatives to current chemicals that raise concerns. Chemical substitutions of known hazardous substances should be based on a policy framework for the identification of better alternatives, taking a holistic view, i.e. considering the chemical mixture of the final article. There is a lack of resources dedicated to substitution initiatives among Member States, ECHA and the Commission (Marovac, 2017). Additional efforts are required to research chemical grouping strategies for regulatory purposes, focusing on the systematic analysis of the structural similarities of substances and trends in, for example, computational predictions and other methods supporting such approaches (Marovac, 2017).

Provide financial incentives for innovation towards safer finished (plastic) articles. Funding for research and development in toxicity testing approaches should address the chemical safety of the finished (plastic) articles by assessing the biological effects of the overall migrate (e.g. endocrine disruption, genotoxic and non-genotoxic carcinogenicity, persistence and bioaccumulation and mobility in the environment). Subsequent innovation towards safer alternatives should take into account the finished article.

PART II:

NOVEL SOURCES, DESIGNS AND BUSINESS MODELS FOR PLASTICS IN A CIRCULAR ECONOMY

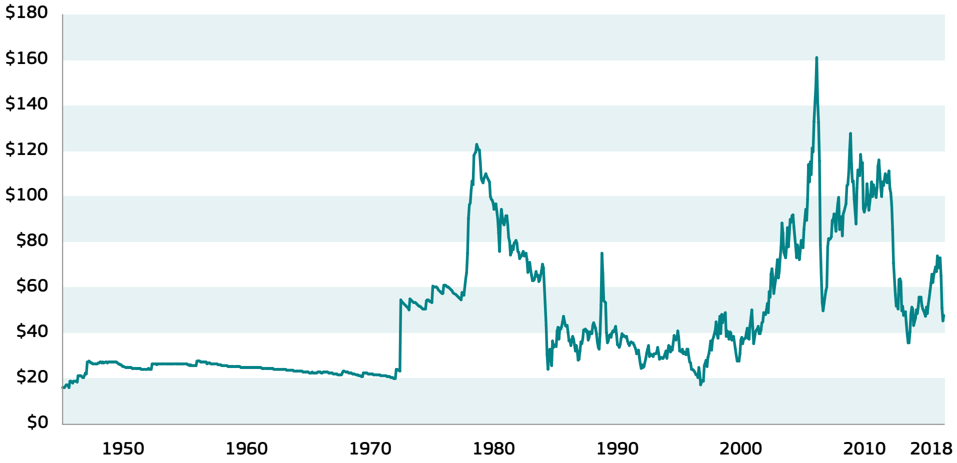
One of the main recognised root causes of plastics value loss and leakage out of the economy is the linear nature of the plastics value chain. Designs and business models requiring short-lived single-use items proliferate, while relying almost exclusively on virgin fossil resources. This part reviews how innovation in feedstock, designs and business models can address this issue.

3 NEW MATERIALS

This chapter focuses on the development of new materials, discussing fossil and renewable feedstock where appropriate. Novel plastics made from the latter often provide an insightful example of the challenges encountered. Renewable feedstock is mostly used to refer to bio-based feedstock, i.e. biomass, biomass-derived by-products, or carbon dioxide (CO_2) or methane derived from biological processes. In this report, the term is also used to denote chemicals from CO_2 or methane captured through artificial carbon capture and utilisation processes (e.g. from industrial-emissions gas or atmospheric carbon). A more in-depth look into bio-based feedstocks is given in Chapter 4. The future of innovation in new materials is driven by a few key present-day insights:

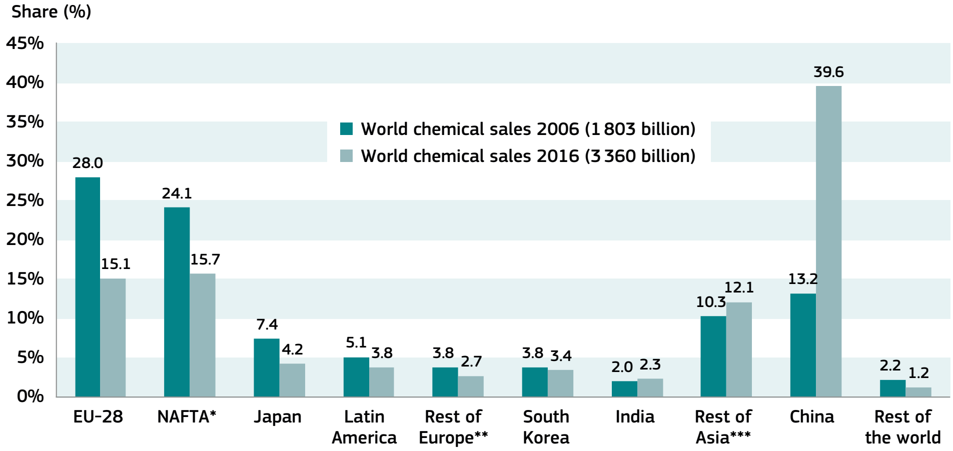
- **Plastics are synthetic alternatives to natural materials.** Plastics have been on the world stage since the end of the 19th and beginning of the 20th century (Morawetz, 1995). The rapid growth of plastics as everyday materials was driven by a need to replace natural product shortages, e.g. ivory and shellac (Pretting & Boote, 2010). Such replacement reflects Thomas Malthus's hypothesis that (unchecked) population growth always exceeds the growth of the means of subsistence (Malthus, 1798). Since its formation in 1968, the Club of Rome has presented and updated a similar hypothesis on the dwindling of the earth's resources its and consequences for a growing global population (Randers, 2012 and Meadows, Randers & Meadows, 2004). To date, plastics have systematically replaced and prevented or helped avoid unsustainable use of natural materials (e.g. metals, ceramics and wood), and the production and use of plastics have grown exponentially in the last decades. Between 1950 and 2015 an estimated 8.3 billion tonnes of plastics were produced, of which 6.3 billion tonnes are considered as waste (Geyer, Jambeck & Law, 2017).

Figure 8: **West Texas Intermediate crude oil prices per barrel in inflation adjusted US dollars from January 1946 to January 2019**



Source: Macrotrends.net, 2019

Figure 9: Overview geographical spread of global sales of the chemical industry in 2006 and 2016



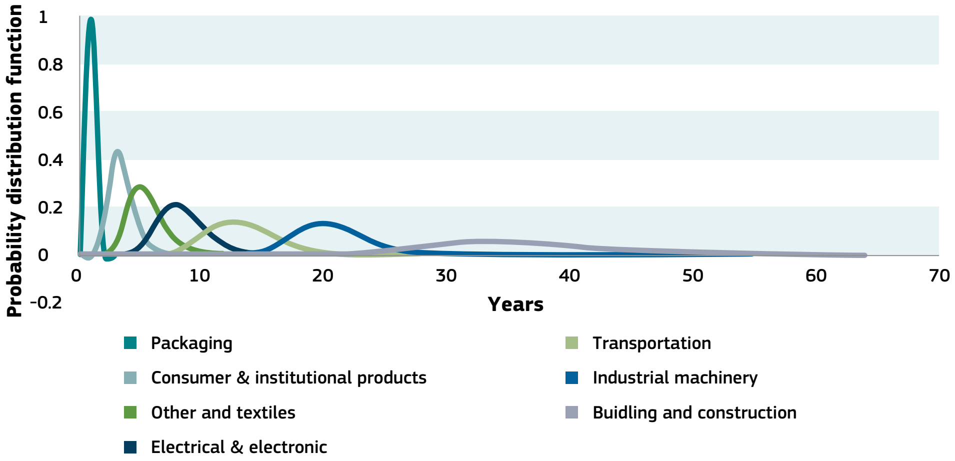
Source: CEFIC, 2018

- **Fossil-based plastics are present all over the world.** The prominent role of plastics, however, is being critically assessed as an integral part of the functioning of society (Geyer, Jambeck & Law, 2017). Today's production volumes are enabled by massive capital investments in gigantic infrastructures and operational mechanisms, rendering plastics cheap materials for mass consumption (Aftalion, 2001; Lokensgard, 2010 and Freinkel, 2011). Plastics production is part of the chemical industry that globally represents EUR 3.36 trillion in sales, with a European share of 15.1 % in 2016 down from 32.5 % in 1996 (CEFIC, 2018). The industry is fuelled by readily available and relatively cheap oil (Figure 8) and has moved from Western Europe and USA to Asia, mainly China (Figure 9). As explained in Chapter 1, not only has plastics production been globalised, but also the challenges, which is an important aspect when considering EU-wide policy.

- **Large plastics waste streams globally are associated with the packaging sector**. A user trend towards more convenience combined with an increase in the living standard of a growing number of people has had a magnifying effect on plastic production. In particular, single-use packages have become a major global environmental burden (Geyer, Jambeck & Law, 2017). Packaging is the largest plastics application, currently representing 26 % of the total volume of plastics used globally and up to 40 % in Europe (World Economic Forum, Ellen MacArthur Foundation and McKinsey & Company, 2016 and PlasticsEurope, 2018). As packaging items typically have very short lifespans (Figure 10) and are directly visible to all in everyday life (Figure 11), the significant amount of plastic waste observed has become a global concern. Obviously, the economic loss and environmental damage linked to plastics go beyond packaging applications.

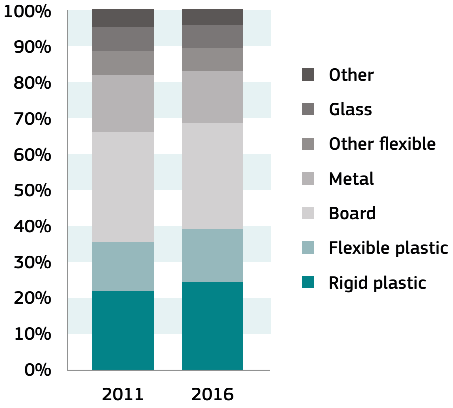
Accordingly, the (manufacturing) industry is trying to address the systemic issues of plastics in a number of ways, including R&I in new materials, scaling up new technologies and innovating the processing and handling of plastics.

Figure 10: **Overview product lifespan distribution for plastics use in different sectors**



Source: adapted from Geyer, Jambeck & Law, 2017

Figure 11: **Shares of different materials in the packaging market, %, 2011 and 2016**



Source: adapted from Page, 2011

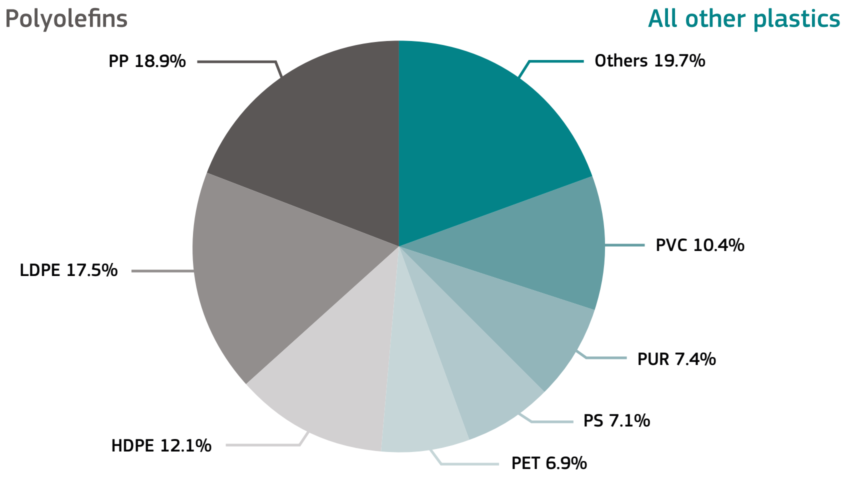
3.1 Novel plastics in an existing chemical industry

State of Play

The present-day commercially available plastics (Figure 12) and associated chemicals are almost completely based on fossil-based feedstock, i.e. produced using oil products, such as naphtha and liquefied petroleum gas, as a precursor (Burdick & Leffler, 1990). The current drive to decouple plastics, as well as economic activities in general, from fossil-fuel dependence has led to a variety of efforts to reduce the need for virgin fossil feedstock.

The plastics industry is part of a complex ecosystem with many different stakeholders and interdependencies, and a vast catalogue of different materials. Different feedstocks produce multiple chemicals and eventually various classes of plastics that need processing to produce products that may eventually be subject to after-

Figure 12: The world plastics use is dominated by few main plastics classes of fossil-based plastics



Source: Fabbaloo, 2018
See 'Acronyms' on page 201

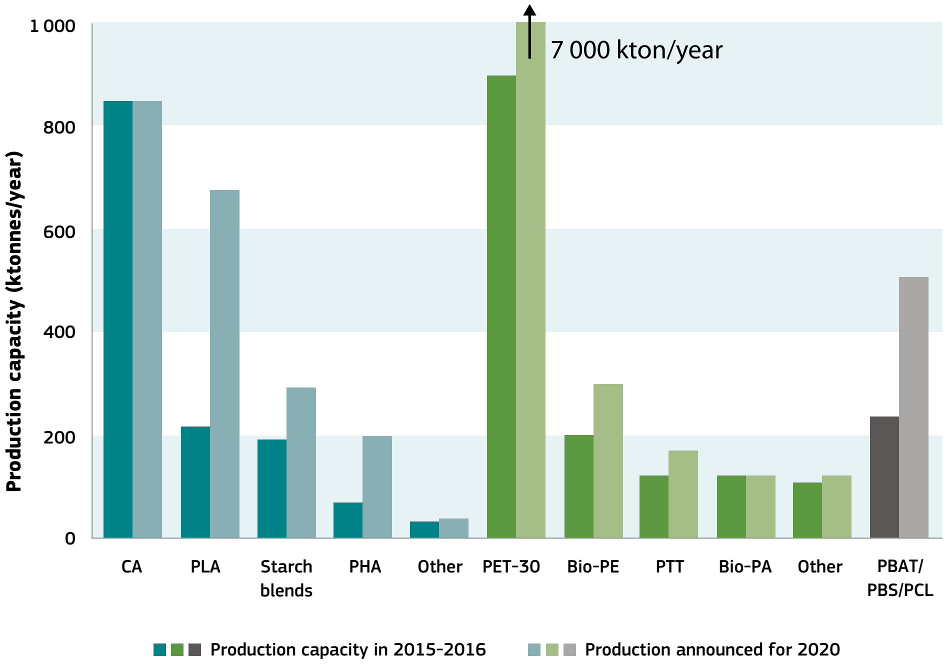
use reprocessing. Production volumes and material prices are to a large extent influenced by the oil industry, which is in turned affected by complex factors including politics, currency and macroeconomic cycles. Polymers are commodities but can be modified in almost endless ways, which has led producers to differentiate to remain competitive. As a result, each class of polymer currently comes in 1 000+ types of plastic with slightly different molecular composition and formulation, depending on the production technology and performance needs. Collecting, sorting and separation of used plastic products thus become very challenging in systems which are not tightly controlled. For example, reprocessing of plastics is much easier inside a production plant than in society, since off-spec material or trimmings are homogenous and in a controlled location. Not only are many different polymer classes and formulations used, material combinations and format design increase the complexity even further. Presently, pathways for circularity provide different options, including reuse, mechanical, chemical and organic recycling (see also Part III of this report, focusing on the after-use system). A key driver of the currently low plastics recycling rate is the material (and design) complexity, making the economics of collection, sorting and recycling challenging (see Chapters 6 and 7 for a broader discussion). It is important to keep in mind the material and industry complexity when discussing the introduction of novel (alternative) plastics to the market.

With plastics linked to oil prices, innovation has historically focused on cost reduction and efficiency improvements whilst increasing versatility of the most widely used polymers. The chemical industry absorbs 7-9 % of global oil supply, with 4-6 % being used to make plastics (PlasticsEurope, 2018). If the world is running out of oil, as suggested by geologist King Hubbert (Hubbert, 1949) and others (Randers, 2012), this is more a matter of potential energy shortages than feedstock for plastics as materials. The production economics, however, are strongly linked to feedstock cost and therefore oil prices.

Plastics producers thus put R&I initiatives in place for reducing production costs, e.g. through better catalysts, reduced emissions, energy savings, site integration, and automation. Some efforts have resulted in expanding the range of properties of a given polymer type. For example, the introduction of homogeneous metallocene catalysis for the production of polyethylene and polypropylene has led to more differentiated and property-tailored products as well as novel elastomeric polyethylene and polypropylene types (Goodall & Benedikt, 1998). The latter, in turn, have enabled a reduction in both multi-plastic products and the use of additives (e.g. cross-linkers and plasticisers), which contributes to making more plastic items recyclable (Benedikt, 1999). Other approaches focus on using inexpensive carbon monoxide or CO_2 as precursors for the synthesis of high-performance plastics or as plastics with specific biodegradability properties, e.g. ethylene-carbon monoxide copolymers and polyketones (FP7 SYNPOL and Toncelli, 2013). The latter was commercially launched by Royal Dutch Shell as Carilon™ in 1996 but production was stopped in 2001. The product was taken up again by the company Hyosung as Poketone™ in 2015 to replace, for example, polyoxymethylene (POM or polyacetal), which is known to form formaldehyde when it degrades (Archodoulaki, Lueftl & Seidler, 2007).

Alternatives to fossil-based plastics include both completely new polymers as well as 'drop-in' polymers made from renewable feedstock. Over the last 80 years, production of fossil-based plastics has grown more than twentyfold (Globe Net, 2018). However, despite relatively strong growth

Figure 13: **Global installed and announced production capacity for selected polymers**



Sources: IFBB, 2016; European Bioplastics, 2016; van den Oever, Molenveld, van der Zee & Bos, 2017

See 'Acronyms' on page 201

recently, plastics based on renewable feedstock represent less than 1 % of the current total volume of plastics commercially offered annually (van den Oever, Molenveld, van der Zee & Bos, 2017; European Bioplastics, 2017b and National Geographic, 2018). As stated before in this report, 'renewable' is used to denote chemicals from biological feedstock or from CO_2 or methane captured through carbon capture and utilisation processes. Figure 13 indicates that statistics and projections can vary, depending on what is included in the definition of renewable. For example, in 2015 PET-30 (30 % by weight) was only partly bio-based via its 30 % monoethylene glycol (MEG) component obtained from ethanol, which was in turn produced using a carbohydrate fermentation process. Some compostable plastics marketed as 'bio-plastics', including polycaprolactone (PCL), poly(butylene adipate)-co-terephthalate (PBAT), and/or poly(butylene succinate) (PBS) are fossil-based. Despite accounting for a relatively small share of plastics production, many privately and publicly funded R&I efforts have been and are devoted to producing plastics from renewable feedstock (Bio-based Industry Consortium, 2017 and Bio-Based Industries Joint Undertaking (BBI), 2018), see also Chapter 4.

Biomass is generally used as feedstock for platform chemicals and monomers rather than plastics directly. Despite its small share of total chemicals and plastics production, renewable feedstock is widely recognised as the long-term alternative to fossil fuels, e.g. as a core principle of Green Chemistry (Sheldon, Arends & Hanefeld, 2007 and Anastas & Eghbali, 2010). Many company and EU R&I Framework Programme projects are developing technologies for using plant-based biomass to extract or retrieve chemicals that are direct replacements for fossil-based chemicals. The efforts are typically related to the biorefineries concept (Fava et al., 2015). Biomass from selected plants (e.g. rapeseed and sugar beet) or waste streams (e.g. bagasse) are used as alternative feedstock for producing platform chemicals that function in existing production infrastructures. In particular, carbohydrates (cellulose and starches) and lignin have been extensively studied, either directly from plants or from plant waste streams. For example, ethylene can be obtained via sugar fermentation and dehydrogenation of ethanol (Mohsenzadeh, Zamani & Taherzadeh, 2017). Other chemicals have been studied in several EU projects, including tetrahydrofuran and furanoates (FP7 ECOLASTANE), lactic acid (FP7 ECLIPSE), succinic acid (FP7 BRIGIT), diacids (FP7 BioREFINE-2G), and 1,4-butanediol and itaconic acid (FP7 BIO-QED). Some of these chemicals have been used to produce bio-PE (from bio-ethanol to ethylene), bio-poly(ethylene terephthalate) (from bio-ethanol to ethylene glycol and lignocellulose-based terephthalic acid) or bio-poly(ethylene furanoate) (PEF, from bio-ethanol to mono MEG and lignocellulose-based furanoates) (Braskem, 2018 and Collias, Harris, Vidhu, Cottrell & Schultheis, 2014). The latter technology was developed by Avantium, which together with BASF under the name of Synvina aims to scale its furandicarboxylic acid production to 50 000 tonnes by 2023 or 2024 (Synvina, 2018 and Chemical & Engineering News, 2018). Similarly, several carbohydrate-based acids can be used to produce monomers such as lactic acid from corn (maize), which can be used to make polylactic acid (PLA) (American Chemical Society, 2009).

Nature provides a range of materials that could be used or modified as alternatives to synthetic plastics, including carbohydrates, proteins and fatty acids/lipids. An alternative to converting biomass to platform chemicals is to view carbohydrates, proteins, and lipids/fatty acids as alternatives to synthetic plastics in their own right (albeit sometimes with some modification of the functionality). Many food and non-food crops, food waste streams and by-products are therefore potential sources of such renewable materials (Kabaci, 2014 and Wool & Sun, 2005). Chemically modified lignocellulose can be used to provide structural and functional products for food and non-food sectors. Wood pulp, grape and olive kernels, coffee grounds, straw and hay, and many more sources are being or have been looked at for direct use as a structural plastic or composite, and potato starch has been used in packaging foil (Kabaci, 2014; Wool & Sun, 2005 and Rodenburg Bioplymers BV, 2018). Similarly, legumes as protein sources or proteins in waste streams of plant and animal origin are being investigated for their direct use. One example is exploiting the functional performance of milk whey as an oxygen barrier in food packaging to replace polyamide or polyvinyl alcohol (FP7 WHEYLAYER). Other proteins such as silk, keratin and elastin are important renewable sources but have attracted mostly academic interest. Also being investigated are omega-hydroxy fatty acids that can form highly polymerised ester-based plastics. These are waxy polymers based on 16-(palmitic) and 18-(oleic) hydroxy fatty acids and applied for coatings in food packaging (FP7 BIOCOPAC).

Challenges and Knowledge Gaps

The chemical industry is complex and fragmented. The view that resources are limited and therefore need careful handling is hardly controversial, but plastics production at scale is still very much a linear business-to-business activity based on a concept of 'product push' and materials replacement (e.g. metals, glass, wood and paper) (McDonough & Braungart, Cradle to Cradle, 2002). Plastics producers are not directly commercially confronted with the after-use processing challenges of the ultimate product made from their products. Multiple intermediate actors design, convert, distribute and use the plastics as products in multiple applications before they reach after-use reprocessing. Collecting and processing either the plastics or their chemicals are, in principle, of no business concern to the plastics producer. It is not clear who is responsible for taking care of the plastic products after use. There is the 'polluter pays' principle (i.e. *Verursacherprinzip*). However, only in exceptional cases for some products are there rules in place obliging vendors to take back the products (e.g. white goods and electronics), depending on legislation in the country concerned (European Commission, 2014b). Moreover, this does not address the responsibility and accountability of product producers in terms of what should be done with the collected products.

No new materials have managed to address the challenge of multilayer materials at scale. Changing the 'product push' into a 'market pull' concept has not altered the linear nature of the plastics value chain (Kim & Mauborgne, 2005 and Heapy, King & Samperi, 2018). Tailoring products to an ever-larger variety of customer needs has led to a multitude of different products with essentially the same function (Hahladakis & Iacovidou, 2018). For example, replacing single-plastic HDPE rigid detergent bottles or containers with lightweight multilayer pouches does save large amounts of material and enables more marketing flexibility. However, the structure of multi-materials makes it very difficult, if not impossible, and economically unattractive to sort and separate the different material components. Consequently, the infrastructure and technology are lacking to ensure adequate collection, sorting and reprocessing for most multi-material or composite products.

The added value of opportunities, such as new functionalities of biodegradable and compostable plastics, is often not valorised when the only aim is to replace fossil-based plastics. When the sole aim is to replace existing fossil-based plastics (e.g. PLA replacing PS for certain applications), then often neither the performance nor production cost of biodegradable and compostable plastics are competitive with the incumbents. This challenge has significantly constrained further development and the required production scaling. Consequently, limited availability and single sourcing has further hampered industry adaptation. However, compostable plastics offer new opportunities going beyond replacing fossil-based plastics, such as new functionalities or facilitation of organic waste collection. See Chapter 9 for an extensive discussion on the role of compostable and biodegradable plastics, and on related opportunities and challenges.

The capital intensity of plastics production poses a major barrier to innovative new materials and feedstock. Plastics innovation and commercialisation has been and still is mainly a matter for large corporations (Aftalion, 2001). It is not necessarily due to a lack of creativity, knowledge or willingness on the part of innovators and entrepreneurs, but mainly related to the capital intensity, organisational structures and sheer scale of the chemical industry. Setting up large-scale plastics production requires careful and long-term geographical planning in relation to feedstock, market accessibility, regulation and legislation, and regional political stability. Even setting up pilot plants for relatively modest production capacity (5 000 to 50 000 tonnes) requires investment of double digit million euros, not to mention the operational cost. The present-day chemical industry is geared to processing vast volumes of oil into fuel, with plastics as a side-stream product. Consequently, the market entry of novel non-fossil-based plastics requires a paradigm shift reminiscent of the change from coal to oil, which took decades to complete.

The direct use of carbohydrates, proteins and fatty acids/lipids as alternatives to plastics remains very challenging despite important progress. To produce these materials, one typically has to deal with mixed biomass feeds (mixtures of carbohydrates, proteins and lipids), compositional variability across growing seasons, volatile availability and the associated development of efficient separation/extraction technologies. Chemically modified cellulose (e.g. cellulose acetate and cellulose nitrate) is mostly based on late-19th-century chlorine technology. New more environmentally friendly chemical approaches need to be developed to replace these technologies (Heinze, El Seoud & Koschella, 2018). With protein and fatty acid/lipid sources, there is a need to develop efficient extraction and separation processes. They are required in purified quantities that can take advantage of their functional and self-organisational capacity to produce novel more versatile plastics. Proteins, for example, develop secondary and tertiary structural organisation that provides product opportunities and a basis for environmental circularity which is not possible with the existing fossil-based plastics (Koopmans & Aggeli, 2010 and Koopmans, 2009). Notwithstanding known and potential advantages of biomass use and associated plastics, a one-to-one fossil-based plastics replacement strategy in the short to medium term is not possible or even needed (Scott, Peter & Sanders, 2007). Rethinking business models and product designs, and fostering efficient collecting, sorting and recycling may go a long way as a first pragmatic step forward (Pretting & Boote, 2010; World Economic Forum, Ellen MacArthur Foundation and McKinsey & Company, 2016; Ellen MacArthur Foundation and IDEO, 2017 and EIT RawMaterials).

The lack of systems thinking reinforces the existing paradigm, hindering market entry of fundamentally novel plastics. A multitude of approaches for innovating plastics and plastics products have been pursued. Each avenue brings its own challenges. However, holistic or systems thinking approaches are rare and considered very risky and challenging to execute and implement. The existing plastics paradigm does not allow for easy market entry of novel fossil- or bio-based plastics. Science and technology can provide many solutions but more critical is the willingness of the many existing actors to change the operational paradigm.

Policy Recommendations and R&I priorities

Policy recommendations

Develop and implement extended producer responsibility (EPR) systems with modulated fees to steer product design towards reuse and cost-effective recycling, and to establish joint value-chain responsibility. Taking into account the application needs, a well-working EPR system should drive product design towards reuse, cost-effective collection, sorting and recycling in the area where the item is put onto the market. This could include a shift towards use of single materials or multi-material products which can be easily recycled. Such a framework could also ensure common responsibility between all participating actors, and risk sharing regarding R&I.

Set up and facilitate investment mechanisms that pool public and private money to consolidate and accelerate the transition towards a circular economy for plastics. Bundle the many scattered efforts into thematic projects to accelerate progress and implementation of business models, products and materials that support the transition. Ensure that the process is clear, and that projects are sufficiently large and financially feasible for investment with a long-term horizon.

Set up a plastics oversight board for strategic planning and long-term investments. Based on the latest R&I insights, such a board could set the strategic direction for policymaking and investments, driving towards a circular economy for plastics. The board should consist of policymakers, topic experts and different types of investors (e.g. project financing, private equity, venture capital and institutional investments).

Provide information and business guidance on applying systems thinking in the context of the plastics value chain. A coordinated support action can help to incorporate systems thinking into R&I activities, such as introducing novel plastics development approaches. A certification programme, building on existing efforts inside or outside the plastics value chain could potentially support uptake of this thinking.

Develop and implement a plastics product information system across the value chain. A barcode-like system would facilitate the identification, collection, sorting and after-use reprocessing, including transparency on additives and potential degradation chemicals. Existing plastics product identifiers are either insufficient (e.g. triangles and green dots) or non-existent. Business-to-business and business-to-consumer users need to be informed about what the product consists of, how it has been used and how it should be dealt with. Implementation of harmonised digital technologies across the value chain would enable consistent and mutually compatible identification and tracking (see also Section 5.3).

R&I priorities

Provide financial incentives to redesign plastic products to facilitate reuse, collection, sorting and recycling. Support design of (plastic) products in relation to the function needed, and to ensure they are easily identifiable (e.g. with after-use handling instructions) to facilitate cost-effective collecting, sorting and reprocessing (e.g. reuse or recycling). Aspects include simplification of the plastic product design in relation to function and benefits, and reduction of the multi-material nature of plastic products. In addition, certification, taxation and tax incentives may drive implementation (see also Chapter 5).

Provide funding for research to develop alternative materials based on the same mechanisms as natural polymers. R&I in this field should develop synthetic chemicals and materials that are more aligned to the functioning of carbohydrates, proteins and fatty acids/lipids in nature. Such chemicals, including additives, and materials are inherently renewable. They are made up of a set of building blocks with multiple uses and often bring environmental benefits. R&I could, for example, use biomimicry (or biomimetics) to apply the same self-organisation mechanism as natural polymers, and develop applications for their direct use and for the production of synthetic bio-based polymers resembling natural ones.

Provide funding to develop infrastructures and technologies that maximise plastics value retention. The infrastructure should enable cost-effective reverse logistics, collection, sorting and recycling of materials. Retention of the material value could be in the form of chemicals, polymers, plastics or products.

3.2 Scaling and commercialisation of new materials and technologies

State of Play

Scaling and commercialising new materials is typically a decade-long process with high risk. Scaling is a matter of developing engineering solutions at an economically acceptable cost typically measured by economic profit and return on investment. Today, the preferred route is the implementation of known and working petrochemical technologies. Some modifications are often included, based on lessons learned from existing operating facilities. Since the early 1990s, globalisation of the plastics industry has entailed the export of these technologies towards regions closer to either a cheap feedstock source or attractive (large) markets, for example the Middle East and Asia (Dow Aramco - Sadara, 2018; Borouge – Borealis, 2018 and BASF, 2018).

Commercialisation of fossil-based plastics passes through existing logistical processes into known market channels. The process is maximised for cost efficiency in a market ruled by supply and demand pricing. Novel plastics, both fossil- and bio-based ones, follow a replacement model through the same existing market channels. Developing new market channels or entering new markets is a very costly and time-consuming effort. For example, using existing market channels, the introduction of novel metallocene catalysed PE took 10 to 15 years. This period, which represents almost the entire lifetime of a patent, is how long it took multiple producers to reach commercially attractive production volumes of several million metric tonnes, with for example global PE volume projected to be 99.6 million tonnes for 2018 (Statista, 2018; Benedikt, 1999 and Chum & Swogger, 2008). The commercial development of novel PLA was initiated by Cargill in the mid-1990s, which was already a feedstock producer of lactic acid from corn. In 1997 they joined forces with the Dow Chemical Company to develop and market the product (Dow Jones, 1997). Twenty years later, with new companies having entered the market, the production volume is only about 200 000 tonnes/year (Figure 12). Also, the experiences of Imperial Chemical Industries (ICI), Monsanto and Metabolix with PHA and of Royal Dutch Shell with polyketones, which are given below, suggest that so far novel plastics have invariably been high-risk commercial undertakings. Moreover, scaling and commercialisation of novel plastics takes a very long time and continued major operational investments.

While further progress on product development and cost competitiveness would benefit their scale-up, bio-based plastics are already suitable for a large number of products. Packaging, catering, consumer electronics, automotive, agriculture, toys and textiles are all possible areas of application (Lambert & Wagner, 2017). For example, PLA is suitable for the same applications as conventional PE: packaging materials, insulation foam, automotive parts, textiles and non-wovens (Bio-Based EU, 2016). Packaging is the largest field for bio-based plastics, with almost 60 % of the total bio-based plastic market in 2017 (European Bioplastics, 2017b). Bio-based polymers derived from different renewable feedstock have been intensively studied in European framework programme projects. In general, it can be summarised that a variety of feedstock provides valuable sources of materials and chemicals for different application areas. In many cases, the potential applications are still in the research phase. However, intensive development work means that new bio-based plastic products are also currently being introduced to the market. For example, the companies Neste and Ikea announced that they would launch commercial-scale production of bio-based PP and PE in 2018 for use in Ikea's commodity goods (Bomgardner, 2018).

While overall capacity is increasing, biorefineries still lack aspects of more mature industries, such as the petrochemical industry. The environmental awareness and the many stimulus programmes at regional, national and European level gave rise to 224 biorefineries in Europe in 2017 (Bio-based Industry Consortium, 2017 and Cordis EU, 2012). Some are new initiatives and others are expansions of existing infrastructures dealing with agricultural products (Cordis EU, 2012). Most biorefineries focus on handling carbohydrates, such as lignocellulose and starch, oleochemicals, such as fatty acids/lipids, and bio-ethanol from carbohydrates. This aligns with the European policy for developing a European bio-based industry (Bio-Based Industries Joint Undertaking (BBI), 2018). A strong stimulus has lowered the barrier to using agricultural by-products for developing useful chemicals and bio-based plastics. The latter targets mainly the packaging market (Bio-Based Industries Joint Undertaking (BBI), 2018). Still, the integration of production plants and sites lags behind the petrochemical industry. Accordingly, there is still little commercial incentive to make additional investments in increasing production volumes and building larger integrated production sites (Bennett & Pearson, 2009 and Oezdenkcia et al., 2017). Besides the conventional chemistry of cellulose modifications, there are hardly any scaling efforts for producing large volumes of novel plastics (> 200 000 tonnes/year). Furthermore, as biorefineries are scattered all over Europe, it is harder to reach economies of scale in feedstock distribution and processing (Bio-based Industry Consortium, 2017). Hence, more regional, decentralised and economically attractive business models should be developed in conjunction with supply logistics.

Significant efforts have gone into the development of biodegradable or compostable plastics from fossil feedstock. In addition to investments in processing biomass as a source for chemicals and plastics, significant R&I capital investments have been made to develop biodegradable or compostable plastics from fossil-based chemicals. PCL, PBAT and PBS are common fossil-based biodegradable polymers that are already widely used in compostable products such as plastic bags. While their biodegradation properties could be similar to those of bio-based biodegradable polymers, the latter category typically shows advantages in terms of global warming (Weiss et al., 2012 and Carus M., 2017), and see also Chapter 9.

Microbial production of biodegradable plastics has been known since the 1980s but has not (yet) reached commercial viability. At the end of the 1990s, the focus on industrial biotechnology inspired researchers and companies to explore the direct use of (genetically modified) microorganisms (Koller, 2016) and plants for the production of plastics. However, as early as the 1980s, aliphatic polyesters of the polyhydroxyalkanoate (PHA) class were being developed by ICI using genetic modification. Monsanto tried to commercialise the plastic, but cost, processing and product performance challenges led it to abandon production (Koller, 2017). The direct use of plants for PHA production has been extensively studied (Somleva, Peoples & Snell, 2013). For example, in 1992, Metabolix tried to commercialise a direct-plant-based PHA synthesis technology. After many years of trying to commercialise the plastic, the company's activities were refocused on becoming an agricultural bioscience company (Yield10bioscience, 2018). Several start-up companies are revisiting these types of polyesters and trying to provide a cost advantage, such as Mango Materials and Full Cycle Bioplastics (Mango Materials and Full Cycle Bioplastics).

It is recognised that increased system complexity poses a barrier to introducing new materials, since handling small volumes is challenging. In 2016, 41.6 % of the 72.7 % recovered post-consumer waste was burned in Europe, illustrating the challenge of handling the increasing complexity of today's plastics system (PlasticsEurope, 2018). Recent policies and strong media attention, however, have raised awareness about the need to include systems thinking in publicly and privately funded R&I projects (EarthDECKS, 2018 and Ellen MacArthur Foundation, 2018b). This should address scaling and commercialisation issues, as large volume production needs effective approaches for large volume after-use handling and sorting (FP7 ULTRAVISC, and FP7 NANOFLEX). The relatively small streams of novel plastics, when introduced to the market, require special attention and different handling or need to fit into existing after-use streams and processes.

Advancing technologies need continuous support for successful commercialisation. Since 1990, multiple EU R&I Framework Programme projects have addressed materials technologies, including scaling of production and after-use product handling (European Commission, 2018g). However, it remains hard to extract from the significant body of work what the eventual impact and the technologies implemented might be. Many projects arrive at a Technology Readiness Level (TRL) 1-5 within a timeframe of 3-5 years. As public funding stops, further development efforts and risk-taking beyond prototypes or pilots towards full scaling and commercialisation is left to industrial partners. In most cases, no further action is taken for the reasons described above. Equally, retrieval of the knowledge generated becomes close to impossible if it is not published in journals or patents. However, one example that shows it is possible to achieve commercial success is the FP7 PLASMANICE project. It gave a commercial boost to industrialising atmospheric plasma technology as a benign plastics' surface modification technology. The technology has now been transferred to industry.

Challenges and Knowledge Gaps

There is a lack of systems thinking in plastics manufacturing. The *Cradle2Cradle* authors define elimination of waste as 'design[ing] things – products, packages, and systems – from the very beginning on the understanding that waste does not exist' (McDonough & Braungart, 2002). In nature, no materials or building blocks are 'waste' after having fulfilled one function. Structural materials like carbohydrates, proteins and fatty acids have evolved to fulfil multiple functions and be cycled perpetually within the system. In contrast, the fossil-based plastics economy has traditionally focused on functionality during use, with no real effort to design a system that works overall. Therefore, systems thinking and developing plastics with the after-use and perpetual reutilisation in mind is poorly developed and understood, which can be seen as one reason behind the mounting plastic pollution problem (Pretting & Boote, 2010; Freinkel, 2011 and Geyer, Jambeck & Law, 2017).

There is a lack of coordination and consistency over time of ongoing efforts. Rising awareness of the challenges of the plastics economy has led to many initiatives to both tackle them directly and generate more knowledge of how to address them. Yet, society as a whole has not taken enough measures to change the status quo. It is crucial to develop a strategic intent for plastics production for use in a circular economy, based on the collected body of knowledge. However, this requires a better coordination of efforts between multiple stakeholders, e.g. bringing multiple disciplines including non-technical experts together, and developing and executing an actionable strategy. Funding initiatives to address plastic pollution are often limited in time, although the systemic nature of the challenge needs consistency over a longer period. European-level initiatives need to be reinforced at a regional level and adapted to specific local economic strengths for wealth creation.

It is unclear what role the fossil-based chemical industry will play in the transition towards a circular economy for plastics, and whether or how this could be encouraged or enforced. In the context of novel plastics developments, the efforts made to address environmental and social issues have often been overruled by other interests, which is one of the reasons for the current state of affairs. For example, by exporting the same technologies to developing economies an industry is likely to export the associated negative impacts already known in developed countries. For a successful transition towards a circular economy for plastics, and the accompanying creative destruction, it is important to understand what role the incumbent fossil-based industry could and should play, and how it can be incentivised or enforced through policy measures.

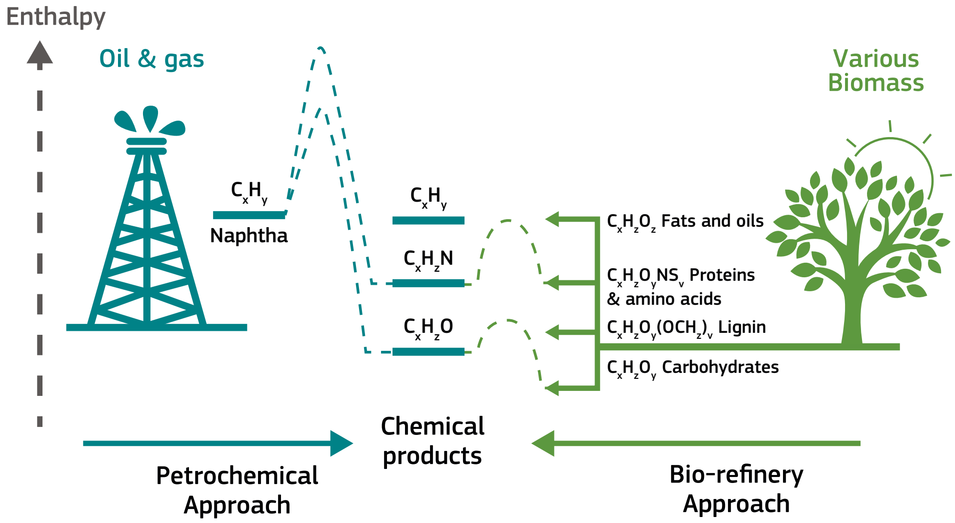
Biorefineries are currently more of a base chemical producer, rather than an integral part of a circular economy for plastics. The biorefinery concept needs integration and consolidation of technologies, including the understanding of different modes of operation – distributive versus centralised (FP7 BIOCORE, FP7 SUPRA-BIO and FP7 EUROBIOREF). In addition, the present focus on mainly carbohydrates is too narrow to capture the full potential of the bioeconomy. Biorefineries need to achieve scale and cost-efficiency to remain economically viable, and understand their role in new circular business models (Agbor, Carere, Sparling & Levin, 2014). The knowledge to make that happen will require a systems thinking approach. Consequently, biorefineries integrated into local areas need expanded interconnectivity to function as starting points for new partnerships and alliances to create circular value chains.

Biomimicry as a base for large-scale plastics production and achieving system circularity is not practiced in industry. A major knowledge gap exists in the application of nature-inspired principles for plastics production. In fact, only limited research results are available on the development and production at scale for eventual commercialisation of such novel plastics (Benyus, 2002). The concept of biomimicry suggests producing plastics that show a functional behaviour similar to natural polymers – carbohydrates, proteins and lipids/fatty acids. The present fossil- and bio-based plastics industries use covalent chemistry. Nature has designed polymers such that properties are defined and enabled by levels of organisation which, depending on the environment, can be reversibly triggered. This means that such plastics have the versatility and ability to be tailored to product performance needs, and by applying specific condition after use they can be reduced back to their base structure and/or building block components (Gebelein, 1993; Bar-Cohen, 2011; Swiegers, 2012; Koopmans & Aggeli, 2010 and Koopmans, 2009). Such reversibility offers the potential to handle novel synthetic plastics just as nature handles organic matter, so that they eventually end as food or feed. This particular strand of systems design would benefit from more attention as such plastics are inherently fit for circular use. Some early examples include ureidopyrimidinones and vitrimers (Mellany Ramaekers, 2014 and Bethany Halford, 2017).

Not enough effort has gone into making use of structural polymers from nature. Naturally occurring polymers (carbohydrates, proteins and fatty acids/lipids) are available in very large quantities as biomass and are hardly (in comparison to fossil-based plastics) used or considered as a direct plastics source. Beyond looking at biomass as feedstock for chemicals, present-day technology makes naturally occurring polymers very viable options as materials for many product needs (Wool & Sun, 2005 and Kabaci, 2014). The chemical richness offers alternatives for more functional and easier to handle plastics with less or no pollution impact as a product (in contrast to synthetic polymers, as explained above). However, the engineering challenges of scale are related to efficient biomass separation and extraction techniques. Such an approach is more attractive energy-wise than attempting to obtain chemicals from biomass that are subsequently used to produce the same fossil-based plastics (e.g. bio-PE). Figure 14 indicates that it is thermodynamically unfavourable to reduce complex natural polymers to the base fossil-based chemicals such as ethylene or propylene to reproduce existing plastics. However, direct use of more complex natural molecules as polymer or fragments thereof is favourable for building renewable plastics and products for a circular economy (Scott, Peter & Sanders, 2007).

Collaboration between engineering and social sciences is too limited. Different perspectives can inspire creative solutions, also in the field of new materials development. Engaging social and behavioural experts with scientists and engineers can bring about innovative product designs, novel plastics developments, and handling approaches more adapted to multiple plastics stakeholder acceptance and ease of implementation. Typically, brand owners and marketing functions deploy such skills but R&I functions rarely do. The fundamental change required to move towards a circular economy for plastics will need to consider the behavioural patterns and societal aspects related to scaling solutions, e.g. cultural and regional differences. Equally, information and communication technology experts can provide

Figure 14: Thermodynamic considerations comparing production of fossil- and bio-based chemicals



Source: Scott, Peter & Sanders, 2007

additional insights and tools to enable a circular economy in which the entire stakeholder group participates.

Policy Recommendations and R&I priorities

R&I priorities

Provide financial incentives and support systems to ensure continuity for implementing industrially attractive R&I projects on alternative processes and/or materials. Alternatives for a plastics industry defined by globalised, highly efficient production facilities producing large volumes of low-cost fossil-based plastic products is going to be a very long process (20-30+ years) and affect global society. To scale and commercialise alternative processes and/or materials, continuity of support is needed beyond TRL 5, for example for large-scale demonstrations and commercial implementation. In addition to financial metrics, such support needs clear criteria for assessing the project's contribution to the transition towards a circular economy.

Provide business guidance to incorporate behavioural sciences, digital, marketing and commercial expertise in R&I projects. In this way, innovative solutions in business models, products and materials would be better positioned and enabled for creating social and economic impact.

Provide funding to develop educational programmes and to stimulate multidisciplinary exchanges. This funding should bring together scientists, engineers, environmentalists, economists, ICT experts and social scientists in the development of alternative economies and systems with associated technologies based on circular economy principles.

Provide funding for investments in strategic infrastructure for the production at scale of novel nature-based plastics. An ecosystem must be built that integrates feedstock, plastics, products, and after-use handling to achieve full circularity with biomass-based produce.

3.3 Novel processing and handling technologies

State of Play

Despite increasing public environmental awareness, plastic products have become more complex rather than more environmentally friendly. Over the last 60 years, public environmental awareness has been on the rise as seminal books, popular documentaries and journal articles have pointed out the societal challenges associated with plastics (Carson, 1962; Donella H. Meadows, Meadows, Meadows, Randers & Behrens, 1972; McDonough & Braungart, 2002; Freinkel, 2011 and BBC, 2018). A drive for regulation and legislation was stimulated, alongside initiatives to reduce, reuse and recycle plastic products. Consequently, this has resulted mostly in safer but only 'less bad' plastics and plastic products, i.e. improved plastics and products but essentially the same concept with improved performance (McDonough & Braungart, 2002). Simultaneously, the drive for product differentiation and cost reduction has stimulated the use of multi-materials. Novel and ever better processing technologies have symbiotically enabled and accelerated such evolution. As indicated in Figure 8, feedstock cost spikes provided the incentives. Accordingly, more high-performing but equally more complex products have been created: lightweight products with multiple materials, composites with carbon, glass or natural fibres, and hybrids combining inorganics with multiple plastics, which are extremely challenging products for after-use handling (see Part III of this report).

Many R&I projects deal with plastics innovation, but most focus only on narrowly scoped material aspects. While thousands of (EU-funded) projects have dealt with plastics, only a few, mostly recent projects specifically focus on systemic aspects of this material. Examples of the latter include H2020 CIRC-PACK and H2020 PLASTICIRCLE, which aim to study circularity of plastic packaging and its after-use channels. Another observation is that the complexity of the plastics industry landscape seems to break down into specific topical challenges. This translates into projects which address the same challenge in different ways, but with limited or no interaction between the actors in the value chain. For example, the barrier properties of food packaging are important in terms of food shelf-life and preservation. They define the performance of multi-material lightweight pouches that are the most difficult to handle after use. EU-funded R&I projects that intend(ed) to address this challenge include FP7 NANOBARRIER, FP7 BANUS, FP7 BIO4MAP, FP7 MEATCOAT, FP7 WHEYLAYER, FP7 WHEYLAYER2, FP7 SUCCIPACK and H2020 BIOSMART.

Significant capital investment requirements for new kinds of processing hinder the scale-up of potentially beneficial new materials. Existing plastics processing and product handling technologies tend to prevail over novel methods unless, besides cost savings, major performance benefits are perceived. Typically, introducing a modified or novel plastic to converters requires processability on existing infrastructure. In one example, a novel plastic introduced to the market performed well without the need for cross-linking, thus eliminating the use of peroxide or silane cross-linking additives – a significant cost saving – as well as the use of hazardous chemicals. This, however, required the resetting of extrusion processing conditions and capital-intensive investments in new extruders (Schramm & Jeruzal, 2008). Another case in point is the introduction of bio-based polyhydroxybutyrate (PHB), or a copolymer thereof, for bottles made in an extrusion blow moulding process (Roy & Viskh, 2015). The operating window for PHB and associated copolymers is only 2-3 ºC due to the narrow melting profile. Very precise temperature controls are needed, mostly irrelevant for the incumbent HDPE. Furthermore, it was found that after processing, the PHB shows a slow recrystallisation behaviour making the bottle brittle and useless for the intended application (FP7 PHBOTTLE).

Alternative approaches have been studied to combine plastic synthesis and processing in one device. In the FP7 INNOREX project, an adapted twin-screw extruder is equipped with an ultrasound microwave device to synthesise and extrude PLA simultaneously. In the FP7 PLASMANICE project, atmospheric plasma-induced surface modification is integrated in-line with the extrusion process to eliminate off-line product handling and the use of solvent-based primers for better surface printability. Over the last 50 years, extrusion (single or mostly twin screw) has become a common technique to chemically modify existing plastics, e.g. ionomers (such as zinc modified ethylene acrylic acid copolymers) or grafted polymers (e.g. using maleic anhydride).

Digital modelling and control mechanisms can be used to improve existing processing technology operations and to enhance production consistency. The use of digital tools for modelling and simulation has only recently started to open up important opportunities. It is a means of handling complex systems and exploring alternative solutions or validating potential options. Likewise, new digital technologies can help design products, reduce scrap and enhance production efficiency. For example, FP7 INNOREX uses flow simulation tools to optimise and monitor the synthesis and extrusion conditions for PLA. FP7 MMP and FP7 F^{3}FACTORY are multiscale materials and manufacturing modelling efforts that aim to improve the performance of plastics. Also, H2020 EMMC promotes the use of materials modelling, including all aspects of plastics modelling, and the integration of scientific and business scenario simulations.

Challenges and Knowledge Gaps

There is a lack of technology oversight. Since 1990, based on the number of projects, a massive amount of science and technology knowledge has been and is being developed (European Commission, 2018f). The overarching coordination and complementarity of implementation technology options remain elusive, or at least, not very easily made tangible for stakeholders due to the lack of overview of where they sit in the technological landscape and what they have accomplished.

Established processing infrastructure is a barrier to market entry that is hard for novel technologies to overcome. The introduction of novel or improved plastics is often inhibited by the existing processing technologies. Innovative plastics developments need to take into account processing with existing equipment or provide a completely new integrated system. Companies prefer not to be locked in with a single producer and prefer multiple sources, which further complicates introducing new technologies. Accordingly, alternative future plastics need to be tailored to available processing technologies. A better understanding is needed of the relationships between the molecular architecture, flow characteristics and processing performance of plastics. Advanced modelling tools, open databases and analytical facilities can assist in avoiding lengthy and costly processing experimentation. In essence, this requires all the actors in the value chain to make a greater communication and coordination efforts.

Present plastics processing technologies are insufficiently flexible to easily adapt to novel materials. For the main part, plastics processing is essentially based on 19th-century concepts of extrusion, casting and forming. It has developed into a high-precision industry with equipment that has been optimally scaled for minimising costs and maximising product performance and quality. This has enabled mass production of single-use and convenience plastic products. The focus on high processing differentiation and fossil-based plastics has restricted the processing flexibility, in particular for processing novel plastics or natural plastics. For example, simplifying multiple packaged goods, reducing multi-materials packaging or facilitating renewable plastics use will require reconsidering the present plastics processing technologies, at least in terms of processing conditions.

No viable processes exist at scale to handle thermosets and cross-linked thermoplastics. The processing and handling of plastic products that have a longer lifespan than packaging (Figure 10) also needs due attention. Of specific importance are products based on BPA-based PUR or epoxy thermoset plastics and cross-linked thermoplastics. Their safe after-use handling is a critical issue. Simple extrusion reprocessing is not possible and resource recovery implies handling potentially toxic chemicals. Alternative replacement solutions need exploring, with renewable chemical options that are safer and easier to integrate into a circular economy. Many PUR and epoxy applications include multi-materials composites, prompting solutions for recovering the valuable glass or carbon fibres. For instance, modern windmill blades are glass-fibre- and epoxide-based composites. The recovery of fibres and resin requires safe and economically attractive solutions, even after a functional lifespan of 50 years. A handful of EU-funded R&I projects have facilitated the development of technologies to recover such high-value fibres, including H2020 R3FIBER. The automotive industry is moving towards lightweight materials to reduce energy consumption – a trend which is reinforced by the shift to electric vehicles, as the heavy batteries in electric vehicles need to be compensated for to maintain a reasonable operational driving distance. Multiple materials, including different kinds of steels, aluminium and (carbon) fibre composites, have to be joined together with structural epoxy- or PUR-based adhesives. The advantage of this gluing is that it is easier to separate the different parts, but then this also involves handling BPA-based structural adhesives. The most practiced technology of energy recovery creates its own challenges through toxic residuals and emissions handling. Cross-linked thermoplastics products pose similar processing and handling challenges. For example, many lightweight sport shoe soles are thermoplastic PU (TPU) or cross-linked polyolefin-based thermoplastics. Electrical or optical cable sleeves can consist of cross-linked thermoplastics or plasticised PVC. The latter poses a range of challenges for handling after use, including chlorine-containing decomposition products and heavy metal catalyst residues such as cadmium and tin (Plinke, Wenk, Wolff, Castiglione & Palmark, 2000). All cross-linked and thermosetting plastics are formulations that contain a multitude of additives. Significant work needs to be done in order to avoid their use, find environmentally friendly and safe alternatives or use closed-circuit processes for mechanical or chemical recovery. A few EU-funded R&I projects have addressed the challenges of finding methods to recycle or make renewable, easy-to-handle highly cross-linked products (FP7 FIBIOSEAT and FP7 FREEFOAM).

Formulation and processing of plastics is based on old technology. All plastics are formulations, i.e. mixtures of multiple chemicals including polymers. The extensive use of additives to formulate base polymers is motivated by the relatively small menu of polymers in use for countless applications. However, the established plastics chemistry and processing technologies date back to the beginning of the 20th and even 19th century respectively. Revisiting the processing and product design technologies is needed in order to replace or avoid unnecessary additives in existing or in combination with novel polymers. Alternative plastics may need alternative processing or product shaping technologies. Additive manufacturing is becoming an accessible approach, for example with 3D printing. Still, 3D printing technology needs to operate with existing plastics that put constraints on the products, applications and economics (Slick, 2018). Other processing challenges relate to assembly of parts, connectivity of parts (welding and gluing), multi-materials parts, types of adhesives, coatings and printing inks, and labels. These aspects relate to challenges of easy disassembly after use, connecting multi-materials (steel with plastic), reinforcing existing plastics, structural adhesives of cross-linked plastics for high-performance applications, protective layers for corrosion or abrasion, and identification and enhancing aesthetics of product parts (see Chapter 5 for an extended discussion on product design).

Development of novel processing technologies requires open access to the latest insights and state-of-the art knowledge. The formulated and processed final plastics product is often a very different material from the synthetic organic macromolecules sold as polymers due to its formulation recipe. Access to information about each value-chain stakeholder's operation and contribution to the formulation of the final functional product is needed in order to apply a systemic approach to how to best design, process and reprocess plastics. For intellectual property (IP) and competitiveness reasons, industry actors find the request to openly share such knowledge a difficult one. Since the overall gains are significant, it is imperative to explore how information transparency can be increased (see Section 5.3). The open innovation concept promoted by Henry Chesbrough aims to foster a sharing culture (Chesbrough, 2003). However, it appears that there are important barriers to companies sharing knowledge. Besides issues with IP, non-agile organisational structures also hinder openness. As a result, limited cross-industry exchanges take place and most 'open' interactions are between actors in the same industry segment. Alternative mechanisms, levers or incentives need to be found to enable processes, methodologies and technologies to be shared across value chains dealing with plastics, and beyond.

Digital technologies in production and logistics have been implemented, but materials and processing modelling are hardly ever used to explore alternative chemistries and product design in a virtual space. Digital technology can facilitate a systems thinking approach to innovate plastics for a circular economy. Internet connectivity and smart algorithms provide methodologies for optimising existing and developing modified or new processing facilities in relation to performance needs and their consequences for after-use issues. Equally, the internet facilitates the gathering of all relevant value-chain actors to jointly develop science and technology in a common open 'marketplace'. It may assist in addressing the complexity of plastics.

Policy Recommendations and R&I priorities

Policy recommendations

Provide financial incentives to selective industries in the plastics value chain to convert to a circular economy based on recycled plastics or biological feedstock. It is crucial to identify and influence for each plastics value chain the ultimate decision makers on the product design (e.g. brands, retailers or converters). Plastics processing is the crucial link from polymer to formulated plastic and final product for use. By ensuring the products (or packaging) are fit for a circular economy, all actors will positively influence the overall transition. Past similarities are the conversion of industries from coal to oil, or from nuclear to renewable energy. Such transformations affect many in their operational existence, for example through the creative destruction process, and finding alternatives can support the transition.

Develop and implement digital techniques to register and follow which actor added what substance to a product throughout the supply chain. These tools should be developed and integrated into existing and alternative supply chains to monitor the polluter-pays principle approach, holding all actors accountable for the products they produce or reprocess. Such a reporting platform or database should ideally be harmonised at a European level to reduce the additional burden on companies, especially start-ups and SMEs.

Set up and maintain a collaboration platform and open marketplace for science and technology exchange related to plastics. Such a mechanism, facilitated by digital tools, should foster research and innovation in this field (including EU-funded projects), accelerate the development of systemic solutions and enable shared risk-taking. Knowledge sharing and communication should stimulate the faster implementation of novel plastics and processing technologies.

R&I priorities

Provide financial incentives to safely recycle or replace thermoset and cross-linked plastics. As thermoset and cross-linked plastics bring specific benefits, R&I projects should develop alternatives that can be recycled while bringing similar benefits, or they should develop safe recycling processes for the existing materials, subject to a holistic impact assessment.

Provide funding for research into alternative plastics manufacturing and processing technologies that enable value retention. This should be aligned to novel concepts and methodologies for polymer structure creation with reversible features as reflected in biomimetic approaches. Here the processing technology has a critical role in shaping the performance properties of the product in a systematic fashion.

4 BIOLOGICAL FEEDSTOCK

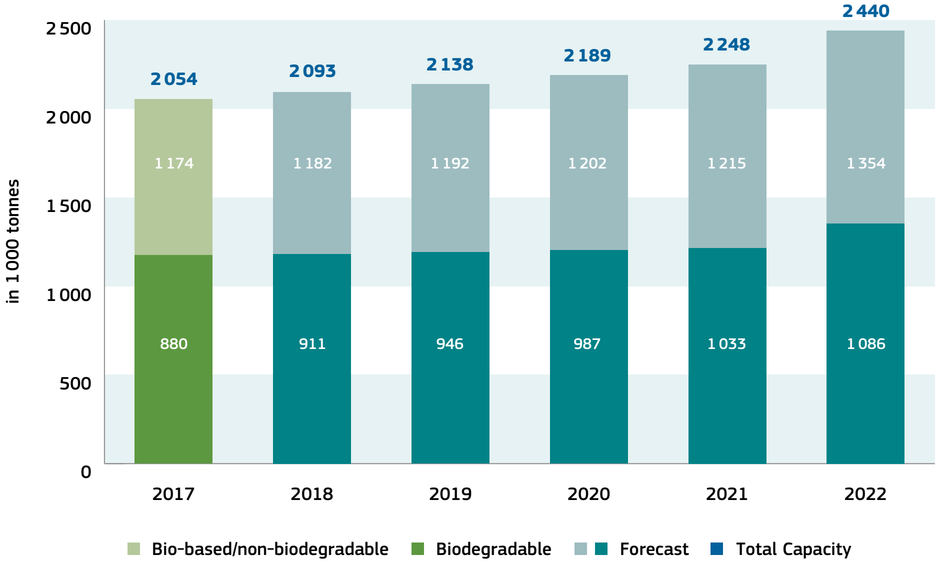
The transition of a fossil-based economy to a bio-based economy is one of the biggest industrial challenges of the 21st century. One of the prerequisites to achieving this transition and decoupling society from fossil feedstock is the development of chemicals and materials from renewable sources, in a way that does not lead to irreversible depletion of natural capital or other negative externalities. In addition, the use of renewable raw materials and resources that today are considered waste is an important part of the broader transition towards a circular economy (FP7 SPLASH and H2020 ReTAPP). Research on bio-based chemicals and plastics has increasingly been carried out in Europe, in line with the 2012 EU bioeconomy strategy, and its 2018 update, and with several bioeconomy strategies from Member States (European Commission, 2012 and European Commission, 2018a). The potential to use chemicals or materials derived from biological feedstock has already been introduced in Chapter 3. This chapter explores the availability of such feedstock, what particular precursors and materials can be derived from it, and the prospects for its products on the market, with a particular focus on plastics. Throughout this report, the term 'bio-based' refers to any polymer, chemical or product that is made of biomass, biomass-derived by-products or CO_2/methane derived from biological processes. In this way, bio-based feedstock is considered a subcategory of renewable or alternative feedstock, which would, for example, also include CO_2 or methane captured through artificial carbon capture and utilisation processes.

4.1 Production of bio-based plastics and chemicals

State of play

While bio-based polymers are expected to grow by varying degrees in the near future, they still represent a small share of the market. Bio-based polymers are a complex group to describe since they contain many different types and subgroups based on their chemistry and properties. They can be 'drop-in' materials chemically identical to some fossil-based polymers or have unique structures and properties (see Chapter 3). Similar to polymers made from fossil feedstock, bio-based polymers can be non-biodegradable or biodegradable, depending on their chemistry (Alaerts; Augustinus & Van Acker, 2018). Currently, bio-based plastics constitute only a small portion (~1 %) of the total world production of plastics (European Bioplastics, 2017b). The global production capacity of these plastics is estimated to increase from 2.1 million tonnes in 2017 to 2.4 million tonnes in 2022 (Figure 15). The share of non-biodegradable polymers, such as drop-in bio-PE, of the total amount of bio-based plastics produced is 57 %, with the remaining 43 % being biodegradable, such as PLA and PHA (Figure 16) (European Bioplastics, 2017b). Under the modest total, there are large variations in growth forecasts across different bio-based polymers (nova-institute, 2018), with biodegradable polymers such as PLA and PHA currently driving the growth. Bio-based non-biodegradable polymers are estimated to remain stable or experience low growth (European Bioplastics, 2017b; Alaerts, Augustinus & Van Acker, 2018 and nova-institute, 2018). According to nova-Institute's studies, the production capacity of PHA is estimated to triple up to roughly 0.15 million tonnes between 2017 and 2022. The production capacity of PLA, which has application areas similar to PE, PS and PET, is estimated to grow by 50 % during the same period. This growth is attributed to improved processing technology and lowered production costs. Clearly, caution is always warranted with this type of estimate, given the complexity. Moreover, the fact that the original amounts are quite small might make growth rates seem large. Estimates cannot be considered facts, and any (bio-based) polymer's development is also affected by factors such as oil price, public opinion and legislation. For example, according to some estimates, the market for bio-PE is growing and the one for bio-PET is not developing, whereas other forecasts suggest a more sta-

Figure 15: Global production capacity trend of bio-based or biodegradable plastics from 2017 to 2022



Source: European Bioplastics, 2017b

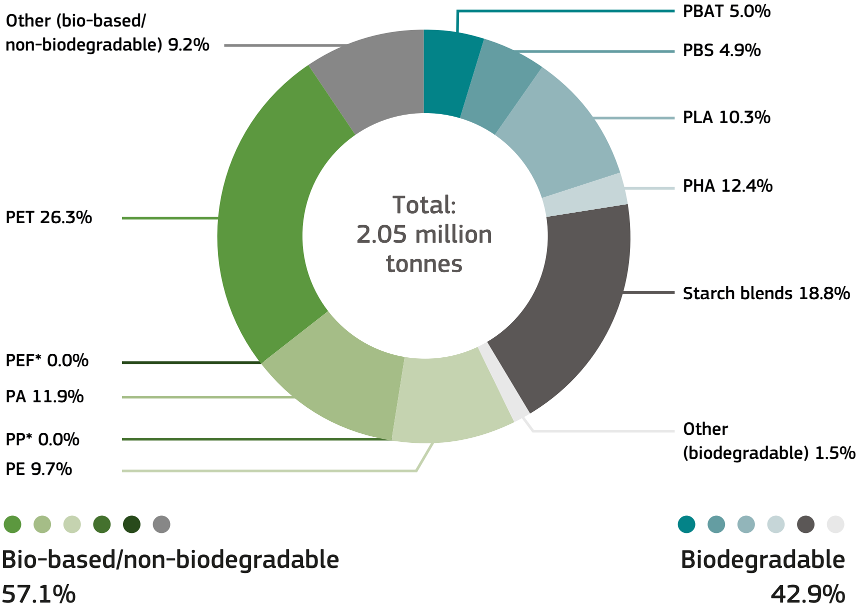
ble development for the former and growth for the latter polymer (Taskila & Ojamo, 2013; Bio-Based EU, 2016; Alaerts, Augustinus & Van Acker, 2018; European Bioplastics, 2017b; nova-institute, 2018 and Institute for Bioplastics and Biocomposites (IfBB), 2017).

More generally, in the next few years the production capacity for bio-based platform chemicals is expected to grow faster than for bio-based plastics. Between 2017 and 2022, the estimated annual global production capacity growth rate is 5-6%, exceeding the estimations for bio-based polymers (3-4% per year). Estimates from EU-funded projects indicate that the market potential for building blocks like fructose, succinic acid, itaconic acid and 2,5 furandicarboxylic acid (FDCA) is increasing (FP7 BIOCONSEPT, H2020 ReTAPP, FP7 TRANSBIO and FP7 SPLASH). Other recent developments in the bio-based chemical area include alternatives for the commonly used epoxy precursor BPA (Lemonic, 2018).

Bio-based materials and chemicals are expected to drive demand for renewable feedstock in the near future. Even though plastics production is still mainly based on fossil feedstock, bio-based plastics have become an increasingly feasible alternative due to improved processing technologies, availability of catalysts and microbial production strains (PlasticsEurope, 2017). According to some estimates, the demand for renewable feedstock for materials and chemicals is currently growing slowly at a rate of 1.5-2% per year in Europe, and 3-4% per year globally. This demand is growing faster though than the demand for renewable feedstock for bioenergy, which has an annual growth rate of 1% globally and ~0% in the EU (Carus & Dammer, 2018). The use of renewable raw materials that today are considered low value by-products or waste is an important part of the transition towards a circular economy (H2020 ReTAPP). Industrial sectors produce a vast amount of side and waste streams, which are currently unused. Additionally, chemical recovery cycles produce biogenic CO_2 and methane that can be captured and transformed into polymers and chemicals using biological or chemical pathways (Boughton, 2014 and Nield, 2018). By converting these streams to valuable bio-based platform chemicals and plastics, the overall resource efficiency would be increased, e.g. as shown by the start-ups Mango Materials and Newlight Technologies (H2020 KaRMA2020).

While it determines the process yield and efficiency, the type of feedstock has limited influence on the performance of the polymer. Bio-based polymers can be produced by three production processes: by the direct use or modification of naturally occurring polymer (e.g. modified cellulose such as viscose), by plant or microbial production (e.g. PHAs) and by polymer synthesis from chemically modified, biological feedstock (e.g. bio-PE or PEF). A wide range of feedstock can be sourced for plastic and platform chemical production. The specific feedstock that the polymer is derived from has been shown not to influence the performance of the bio-based plastics in principle, especially in the case of drop-in chemicals. Performance instead depends on its chemistry (Lambert & Wagner, 2017). However, the nature of the feedstock largely determines how easily the biomass can be converted to different intermediates or products. Bio-based plastics, like their

Figure 16: **Global production capacity of bio-based or biodegradable plastics per material type in 2017**



** Bio-based PP and PEF are currently in development and predicted to be available on a commercial scale in 2020.*

Source: European Bioplastics, 2017b

fossil counterparts, have to meet the performance and functionality demands of a specific application. Examples of the properties needed are good adhesion, barrier properties against water and gases, and mechanical properties such as tensile strength and tear resistance. In addition, the properties and functionality of the bio-based and biodegradable plastics, the demand for adequate yield and consistent product quality are the key issues for industrial process optimisation and scale-up (H2020 COSMOS, FP7 TRANSBIO, FP7 BUGWORKERS, FP7 LEGUVAL, H2020 FUNGUSCHAIN and FP7 WHEYLAYER2).

There is growing industrial interest in 2nd and 3rd generation renewable feedstock. Today, bio-based plastics are mostly made from 1st generation feedstock, such as sugar cane or oilseed plants. While 1st generation feedstock is currently the most efficient feedstock for the production of bio-based plastics, positively affecting both economic and environmental impact, it has shortcomings from the economic, environmental and social perspective (European Bioplastics, 2017c; Alfano, Berruti, Denis & Santagostino, 2016, FP7 WHEYLAYER2, FP7 TRANSBIO, H2020 ReTAPP, FP7 BIOCONSEPT and H2020 Zelcor). Even though some of these flaws can be addressed through an appropriate regulatory framework on the use of agricultural and forestry by-products, the industry is looking in parallel into non-food 2nd and 3rd generation feedstock, such as wood residues, dairy, fruit and vegetable by-products, waste streams and algae (European Bioplastics, 2017c). The 2nd generation feedstock streams are relatively abundant and do not compete with food or feed production. Studies on biofuel production have indicated that while prices for the 2nd generation biomass source vary, this feedstock can compete with 1st generation feedstock on cost. In addition, some forms of municipal solid waste and harvesting leftovers can be sourced at minor expense. Compared to 1st generation feedstock, the environmental benefits of 2nd generation feedstock include the valorisation of industrial by-products or waste streams, and reduction of land-use competition with food or feed crops (Alfano, Berruti, Denis & Santagostino, 2016, FP7 WHEYLAYER2, FP7 TRANSBIO, H2020 ReTAPP, FP7 BIOCONSEPT and H2020 Zelcor).

Challenges and knowledge gaps

Due to the relatively low oil price and vast production scale of petrochemical industries, the bio-based plastics are generally more expensive than fossil-based plastics. The raw material cost is one of the main operating cost factors for bio-based products (FP7 ReTAPP and H2020 BIO4PRODUCTS). For example, in 2013 the price of crude oil was relatively high. Still, due to the biomass feedstock prices and production costs of bioethanol, the price of bio-based PE was still 30-60 % higher than that of PE made from fossil feedstock (IEA-ETSAP and IRENA, 2013). In a cost-sensitive industry, such a difference poses a major barrier to scaling bio-based feedstock as viable alternatives to fossil feedstock. The production process cost is another factor affecting the price of the product, although its role is smaller than feedstock cost (FP7 FORBIOPLAST and FP7 BIOCONSEPT). New and improved approaches to fermentation process design, scale-up strategies, and the reduced number of processing steps enable the mitigation of the price gap of bio-based plastics and chemicals (H2020 COSMOS, FP7 TRANSBIO, FP7 SPLASH, FP7 OLI-PHA and Dammer, Carus, Raschka & Scholz, 2013).

The market demands that the generally higher price of bio-based plastics compared to those based on fossil feedstock be justified by added value, for example better performance or environmental benefits (H2020 BIO4PRODUCTS and H2020 COSMOS). While there are exceptions, such as PEF and certain polyamides, many of the currently available bio-based plastics often struggle to meet the key requirements set for conventional plastics. This especially concerns barrier properties needed for food packaging (FP7 WHEYLAYER2). In addition, limitations in the mechanical properties are typical of some bio-based plastics (FP7 FORBIOPLAST and FP7 LEGUVAL). Moreover, there is often limited information on the differences (or similarities) in environmental or social advantages of specific bio-based polymers and chemicals compared to fossil-based counterparts. Hence, more knowledge is needed on the production of bio-based polymers and chemicals with the potential to be adopted for industrial use in large-volume applications, such as food packaging and mulching film (H2020 FUNGUSCHAIN).

The main technical bottlenecks are related to the efficient processes needed for the scale-up of bio-based polymers or chemicals production. The establishment of large-scale production facilities in Europe has been slow, which might reflect the low readiness of industry to enhance the commercialisation of new bio-based products (FP7 BIOCONSEPT and FP7 FORBIOPLAST). The incumbent plastics industry is a high-volume business with large existing infrastructure, and optimised manufacturing and marketing operations (see Chapter 3). The bioeconomy though will need flexible, small-scale facilities and business models adapted to regional conditions (e.g. supply). The commercialisation of bio-based plastics requires adapted business models for bringing together suitable value chains and market creation potential, new pilot demos, broadened product portfolio and a change in the corporate mindset (H2020 FUNGUSCHAIN, FP7 BIOCORE, FP7 SUPRA-BIO and FP7 EUROBIOREF). The potential for integrating plastic production in biorefinery plants needs to be assessed as modern facilities can use a variety of feedstock and processing technologies to produce a broad spectrum of energy and chemical products, like oil refineries do (Dietrich, Dumonta, Riob & Orsata, 2017). As 2nd and 3rd generation feedstock typically consist of more mixed materials compared to 1st generation, its use currently often involves less efficient production processes. A guiding regulatory framework, including a transitory phase for the use of 1st generation feedstock, could support the scale-up, while mitigating potential negative environmental or social impacts.

Policy Recommendations and R&I priorities

Policy recommendations

Continue to provide financial and regulatory incentives to support the scale-up of bio-based plastics and chemicals to move towards a low-carbon economy. A successful European bioeconomy will help mitigate climate change, manage natural resources, enhance biodiversity and strengthen European competitiveness (European Commission, 2018a). The petrochemical and chemical industries can play a role in advancing the production of bio-based polymers and chemicals, given their existing infrastructure. They could further develop and grow drop-in materials, since no direct changes are needed to production technologies and material choices downstream of the initial feedstock refinement. However, to realise the full potential of the bioeconomy, innovative materials and new dynamic, small-scale, decentralised business and biorefinery models will also have to be developed. The mitigation of the price gap should be facilitated by creating an overarching approach to promote the use of industrial by-products and waste streams instead of virgin feedstock, or by providing economic incentives to move from fossil to renewable feedstock. In addition, mandatory targets, fiscal measures and public procurement can play a role. Agricultural policies need to be aligned with regulations dealing with a circular economy and bioeconomy. These efforts should complement the existing efforts, such as the Bio-Based Industry Joint Undertaking (Bio-Based Industries Joint Undertaking (BBI), 2018).

Develop EU-wide strategic planning for scaling biorefineries related to plastics and chemicals production. Stimulate collaboration or consolidation to create cost-efficient chemicals and plastics producing units integrated in a circular economy. This collaboration also needs to include farmers to ensure a consistent supply.

Provide information for business on the differences and similarities in performance of bio-based polymers and chemicals compared to fossil-based counterparts. This information would enable better decision-making and the justification of possibly higher costs.

Set up an oversight organisation to track existing and expected inventories of non-fossil-based feedstock. In order to understand the potential and feasibility of developing bio-based platform chemicals and plastics at scale, the current and expected inventories need to be known. This overview should also foster collaboration between feedstock suppliers, e.g. farmers, and feedstock converters, i.e. industry.

R&I priorities

Provide financial incentives and investments to ensure continuity for implementing industrially attractive R&I projects on bio-based materials. Long-term R&I investments in the EU have to foster the development of bio-based polymers and chemicals beyond lab scale. Hence, (financial) support should focus on projects that aim to achieve TRL 5 or higher to boost scale-up, commercialisation and market introduction of bio-based polymers and chemicals.

4.2 Economic, social and environmental impacts of bio-based plastics

State of play

Transitioning towards a bio-based society is encouraged by a large number of EU directives, initiatives and regulations. It has been estimated that the transition to renewable alternatives could generate 14 000 full-time jobs (H2020 BIO4PRODUCTS). In general, policies adopted at national or European level are currently encouraging the utilisation of various kinds of biomass as alternatives to fossil-based raw materials for the production of materials and products, and as such incentivising the transition to a bio-based society (FP7 SPLASH). The majority of legislation and standards for a raw material is the same, regardless of its initial feedstock (H2020 KaRMA2020). The Bioeconomy Strategy and the Circular Economy Package are two important initiatives driving the transition towards a circular economy (European Commission, 2012 and European Commission, 2015a). Additionally, the Packaging and Packaging Waste Directive and REACH promote environmental and human health concerns in relation to material use ((European Commission, 2018i), FP7 WHEYLAYER2, FP7 TRANSBIO, H2020 KaRMA2020, FP7 LEGUVAL and FP7 OLI-PHA). The Renewable Energy Directive promotes the use of energy from renewable sources (European Commission, 2009a). Currently, new binding renewable energy targets of 32 % have been set for the EU for 2030 (European Commission, 2018k).

The environmental and social consequences of a growing bio-based market are complex. Factors such as the amount of used water, fertilisers, pesticides (agricultural feedstock), forestry practices (forest), and competition for land use between food, industrial products and fuel production influence the environmental and social impacts of the bio-based products (nova-institute, 2016 and H2020 BIO4PRODUCTS). Renewable feedstock can offer an environmental benefit related to climate change due to its carbon sequestration, which together with other environmental and social impacts can be assessed by using adequate criteria (nova-institute, 2016 and H2020 BIO4PRODUCTS). Different tools, such as Life Cycle Assessment, can support the assessment of the environmental impact of products (Haupt & Zschokke, 2017, H2020 COSMOS, H2020 FUNGUSCHAIN, FP7 WHEYLAYER2 and H2020 FIRST2RUN). However, conventional LCA does not sufficiently take into account the after-use stage of a product, and assigns high penalties to bio-based materials for land use and fertiliser use even though they might be derived from agricultural waste (United Nations Environment Programme, 2018). Following up on the EU Plastics Strategy, the Joint Research Centre is working on LCAs for plastics made from different feedstock materials (Joint Research Centre, European Commission, 2018). The environmental performance (CO_2 equivalent, emission of volatile organic compounds (VOCs) and toxicity indicators) of the bio-based products can be improved by utilisation of better extraction processes, as has been shown with products derived from mushroom and fruit production side streams (H2020 FUNGUSCHAIN and FP7 TRANSBIO). Some waste streams that are suitable feedstock for polymers and chemicals can simultaneously be hazardous pollutants. For example, olive mill wastewaters, a good source of bio-based products, have limited disposal possibilities due to their ecotoxic properties (FP7 OLI-PHA). The increased energy efficiency of the bio-based intermediate production is also an important factor related to sustainability (H2020 BIO4PRODUCTS). Analyses demonstrate that concerning the mitigation of global warming, 2nd generation biomass is a better choice than 1st generation biomass. The former has a Global Warming Potential (GWP) of 137 kg CO_2e/tonne high-fructose syrup, whereas the GWP of the latter is 642-760 kg CO_2e/tonne sugar (H2020 ReTAPP). Cascading use of renewable feedstock usually increases the efficient use of resources. However, the direct connection to a reduced release of GHG emissions is more complex. For example, GHG emissions of organic by-products or waste will only decrease if the emissions caused by the collection, separation and processing of the by-product stream into bio-based products are lower than the emissions caused by sourcing and producing the virgin bio-based product (Carus & Dammer, 2018 and H2020 COSMOS). Studies on the global, regional and local environmental effects of biodegradable packaging have shown that global and regional effects on GHG release into the atmosphere by controlled biological treatment are positive, but locally it can lead to a disturbance in the balance of an ecosystem. In particular, the local effects can be characterised by the accumulation of contaminants (from biodegrading plastics), which can serve as fertilisers or inhibitors for plant growth, both influencing the balance. Changes in land use patterns, e.g. shifting from food production to industrial crops, and related changes in organic carbon stocks of above- and below-ground biomass can have a remarkable impact on biodiversity and the climate (H2020 COSMOS and Fritz, Link & Braun, 2001).

The justified concerns about land use increase and/or competition with food and feed production can be mitigated by moving towards 2nd and 3rd generation feedstock. New uses of biomass can indirectly affect environmental indicators by withdrawing resources from former uses. One of the most common indirect effects is change in land use. If land that was formerly used for food or feed production is then used for the production of industrial crops, it is likely that feed and food production are shifted to other land elsewhere. This can cause clearing of natural ecosystems and hence changes in organic carbon stocks and damage to biodiversity (H2020 COSMOS). A future-proof supply of feedstock is a key requirement for bio-based products. All feedstock practices that have negative effects, e.g. deforestation and competition between the use of biomass for food and its use for materials/energy, should be avoided (European bioplastics, 2016b). Around half the EU's land is farmed and farming is important for the EU's natural environment. Inappropriate agricultural practices and land use can have an adverse impact on natural resources, such as pollution of soil, water and air, land erosion, fragmentation of habitats and loss of wildlife, and needs to be avoided (FP7 FORBIOPLAST). Currently, the production of bio-based plastics utilises 1.4 million hectares of land, which is approximately 0.02 % of the global agricultural area totalling 4.9 billion hectares. If the demand for industrial bio-based products and energy from biomass continues to grow, this could lead to an expansion of global arable land at the expense of other agriculture or natural ecosystems. Therefore, transitioning from 1st to 2nd or 3rd generation feedstock and using by-product and waste streams should be recommended (European Bioplastics, 2017c; European Bioplastics, 2017b; Plastic Pollution Coalition, 2017; nova-institute, 2016; H2020 BIO4PRODUCTS and FP7 TRANSBIO).

Standards, quality control and adequate information foster the market entry and acceptance of new products. Consumer acceptance and choices significantly affect the market entry of bio-based plastics. Public procurement has shown itself to be a powerful tool for promoting and accelerating the market entry, while simultaneously positively influencing consumers' minds (Dietrich, Dumonta, Riob & Orsata, 2017). Market penetration of bio-based products also benefits from harmonised standards with environmental criteria and labels. The International Organization for Standardization (ISO) has created a system to categorise the labels for sustainable products (H2020 BIO4PRODUCTS), while the American ASTM D6866-18 and European CEN/TS 16137 standards focus on the certification of the bio-based content of the products (nova-institute, 2016). The CEN Technical Committee 'Bio-based products' (CEN/TC 411) has started developing standards that cover horizontal aspects of bio-based products, mainly in the scope of green chemicals and materials. Standardisation work is also ongoing in the following areas: common terminology for bio-based products (EN 16575), common methods for determining bio-based content (CEN/TR 16721, CEN/TS 16640 and EN 16785), a common methodology on LCA (EN 16760), sustainability criteria (EN 16751) and tools for communication between businesses and businesses to consumers (EN 16848, EN 16935, CEN 2014b and H2020 KaRMA2020).

Sorting, collection and recycling of non-drop-in bio-based plastics is a challenge and contentious issue. Bio-based plastics, due their complex design and chemistry can create difficulties in the current collection and recycling processes (Plastic Pollution Coalition, 2017). Bio-based plastics, and other new materials, are increasingly being introduced into a range of consumption products, and after their use they often end up in mechanical recycling chains, irrespective of their recyclability. Like many other new materials, non-drop-in bio-based plastics are often not compatible with existing recycling processes, which can lead to decreased quality of the recycled plastic stream (Alaerts, Augustinus & Van Acker, 2018 and Forsgren & Svedberg, 2012). Mechanical recycling (Chapter 7) and organic recycling (composting; Chapter 9) are two different after-use pathways for bio-based plastics. In principle, mechanical recycling provides an effective and easy way of reusing materials. However, efficient mechanical recycling requires a critical mass of plastics to warrant additional sorting capability. In order to secure recyclability, bio-based plastics must either be compatible with existing recycled resins (i.e. drop-ins), or if novel materials they must be available in sufficiently large quantities to achieve the necessary critical mass. Currently, bio-based polymer volumes do not fulfil these requirements (FP7 BUGWORKERS and Souroudi & Jakubowich, 2013), and it is not universally clear how big such volumes need to be. Organic recycling also has its challenges, as compostable plastic items are not always sorted properly at home, or are not accepted by composting facilities in certain regions (see Chapter 9 for a more exhaustive discussion).

Challenges and knowledge gaps

There is still limited knowledge about the ways in which bio-based feedstock can support the transition towards a low-carbon circular economy, and what the related environmental impacts are. The growing concerns about making products from renewable feedstock that competes with the food chain could be one of the major future barriers to the market entry of bio-based plastics (Dietrich, Dumonta, Riob & Orsata, 2017 and FP7 LEGUVAL). Better data to support understanding of the optimised use of bio-based feedstock is needed, e.g. on European and global production capacity, as well as food/feed production versus material/chemical production. In addition, to achieve a holistic understanding of the contribution of bio-based feedstock to a low-carbon economy, the impact of fossil feedstock needs to be further clarified. To promote awareness, concrete narratives and success stories that demonstrate the overarching economic, social and environmental potential would be helpful (Carus & Dammer, 2018). The marketing of bio-based plastics as 'eco' or 'green' sends a misleading message to consumers as such concepts are vague, adding to the confusion. An example of a concrete label for bio-based materials is one that is based on the amount of fossil resources avoided, e.g. measured as CO_2e, but such a metric is complicated both to calculate and to communicate to end users. To be effectively implemented, however, such labelling must be accompanied with a robust standardised way of measuring bio-based content (both from virgin and secondary biological feedstock), especially in the light of bio-based feedstock likely being used in existing chemical processing infrastructure. Several stakeholders are exploring how mass balance accounting could work for bio-based content (ISCC plus, 2016; TÜV SÜD Industrie

Service, 2017 and ProBioTracker, n.d.). Additionally, some consumers avoid buying bio-based products because of concerns about the (bio)chemistry involved and the (perceived) uncertainty about the safety of the products, such as hygienic aspects of products made from poultry side streams (e.g. feathers). Misconceptions and lack of adequate information on the quality of side-stream and waste feedstock can also hold back the transition towards bio-based plastics (Plastic Pollution Coalition, 2017 and H2020 KaRMA2020).

Regulatory and legal frameworks create barriers to the industrial production of bio-based plastics, in particular regarding use of by-products. Currently, the criteria and definition for industrial by-products and waste are complex and unclear, which causes difficulties for the industrial utilisation of by-products and side streams. Moreover, markets are interpreted as being linear by the current legal framework, which complicates the cooperation between value-chain actors and industrial sectors. These issues can hinder development tracks as they result in additional costs and extensive activities, e.g. for product registration, reporting and quality monitoring. The legal liabilities associated with waste management, reuse and recycling and compostability can act as a barrier to the exchange and reuse of waste flows (H2020 FUNGUSCHAIN). Current collection, sorting and preprocessing systems are not designed for bio-based plastics. There is a need to revise them (Alvarez-Chavez, Edvards, Moure-Eraso & Geiser, 2012 and H2020 FUNGUSCHAIN).

There is a lack of a holistic set of metrics and standards to assess and compare the economic, environmental and social impacts of different bio- and fossil-based products (FP7 TRANSBIO and nova-institute, 2016). Currently, the models used in impact assessments for bio-based products are different from those used for the designing of the production. This makes the integration of such assessments into product development difficult and results in a high degree of uncertainty (H2020 BIO4PRODUCTS). EU standards for bio-based products should also cover the determination of bio-based product capabilities that can be translated into specifications (H2020 KaRMA2020, FP7 BUGWORKERS) and (nova-institute, 2016)). It is also important to obtain harmonised quality assurance systems (H2020 FUNGUSCHAIN).

Policy Recommendations and R&I priorities

Policy recommendations

Develop and implement a framework to assess the environmental impact of plastics throughout the entire life cycle. Such a framework should be used to compare plastics made from different types of fossil and renewable feedstock. Development of criteria for quantitative and qualitative impact assessment of bio-based plastics is needed, from raw material supply to after-use reprocessing. Criteria should also cover the entire conversion chain from feedstock to value-added product (FP7 TRANSBIO, FP7-WHEYLAYER2, (Carus & Dammer, 2018; nova-institute, 2016 and Piotrowsky, Carus & Essel, 2015).

Provide information and guidance for business and public procurement through labelling for bio-based materials. Promote the transition through promotional campaigns targeting specific materials and rollout of standards and labels designed for public procurement. Under the EU public procurement directives, contracting authorities can use labels as a source of information for defining technical specifications or awarding criteria (European Commission, 2014c). Develop labels to offer a way to demonstrate technical specifications (H2020 KaRMA2020and nova-institute, 2016).

Develop a comprehensive set of standards for bio-based plastics, building on existing efforts, such as test methods and EU standards. Such standards should determine the type of feedstock, bio-based content (for example based on a (bio)mass-balance approach, or a C14 carbon method), product capabilities, technical measures for recovery processes, adaptation of treatment technologies and optimisation needs (H2020 FUNGUSCHAIN). Building on existing efforts, such as CEN/TC 411 on bio-based products (CEN) and EN 17228 on bio-based plastics (DIN), the set of standards should be comprehensive and incorporate the latest insights.

Invest in public infrastructure to enable collection, sorting and (organic) recycling of plastics after their use, regardless of their feedstock. Similar to plastics based on fossil feedstock, bio-based plastics can be mechanically, chemically or organically recycled (e.g. composted), depending on their chemistry (Alaerts, Augustinus & Van Acker, 2018; FP7 OLI-PHA and FP7 LEGUVAL). To maximise the environmental and economic benefits, they should be properly collected, sorted and recycled, which requires the right infrastructure (H2020 FUNGUSCHAIN).

Harmonise, simplify and develop the legal framework for industrial by-products and waste to facilitate the market entry of bio-based polymers and chemicals. Clarify and redefine the current definitions of by-product and waste to ensure the utilisation of industrial by-products from renewable feedstock.

Provide financial and regulatory incentives to support market formation for bio-based plastics. This could be carried out at European and country level by introducing policies for bio-based products, such as mandatory quotas, tax incentives and feed-in tariffs and premiums. Currently, such measures are used in the energy sector and a similar approach could be used for all bio-based sectors (European Bioplastics, 2017b and European Bioplastics, 2017c). A European policy framework should support bio-based materials and products, similar to the support for bio-based energy, to ensure a level playing field and to avoid market distortion of feedstock availability and allocation (Carus & Dammer, 2013).

4.3 Use of by-products from other processes as biological feedstock

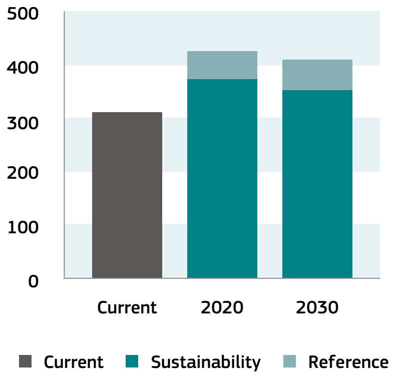
State of play

European biomass potential provides a strong basis for bio-based plastics production opportunities. According to estimates carried out for bioenergy, the current biomass potential in Europe is around 310 MTOE (i.e. million tonnes of oil equivalent, which is the energy unit defined as the amount of energy released by burning one tonne of crude oil) (Alfano, Berruti, Denis & Santagostino, 2016). In general, the availability of renewable feedstock across Member States is good. However, there are great differences between countries and regions in terms of types of feedstock. Northern Europe is dominated by forest-based feedstock, whereas Central and Southern Europe is more focused on agricultural feedstock (Elbersen et al., 2012).

The biomass potential of diverse crops, residues and side streams for the production of bio-based plastics and platform chemicals has been intensively studied in the reviewed EU research projects. The selection of feedstock was carried out according to the R&I interest, regional policy standpoint and availability of the feedstock. The range of European biomass feedstock is vast and diverse, covering oilseed plants, fruit, vegetable and protein by-products from the processing industry, and forest-based feedstock, to name a few examples. In Europe, in 2013 the total area harvested for the production of primary oil crops, such as sunflower, rapeseed, olives and soya beans, was 35.8 million hectares. Camelina and Crambe varieties, plants whose oils could potentially replace imported palm and coconut oil, have shown to adapt well to northern and Mediterranean climates. The seed yields are promising in all test climates. Each year, the European fruit and vegetable processing industry produces around 192 million tonnes of waste and by-products. Whey is an abundant by-product of the dairy industry. The EU produces about 50 million tonnes of whey annually, of which some 40% remains unprocessed (H2020 FIRST2RUN, H2020 COSMOS, FP7 TRANSBIO and FP7 WHEYLAYER2). According to one estimate, 40% of the whey could substitute the global needs for EVOH barrier (ethylene vinyl alcohol) utilised in food packaging (FP7 WHEYLAYER2). Forest biomass is a raw material for a diverse range of chemicals and products (Hetemäki, ym., 2017). Of the total area in the European Union (2008), 177 million hectares (~130 million hectares for use) is forest. Approximately one-third of global roundwood production takes place in Europe. More than 50 million tonnes of lignin annually are derived from different pulping processes and merely 1 million tonnes of the lignin are used commercially. Tall oil is available for further industrial use. The total yield is estimated to be 1.5 million tonnes per year (FP7 FORBIOPLAST).

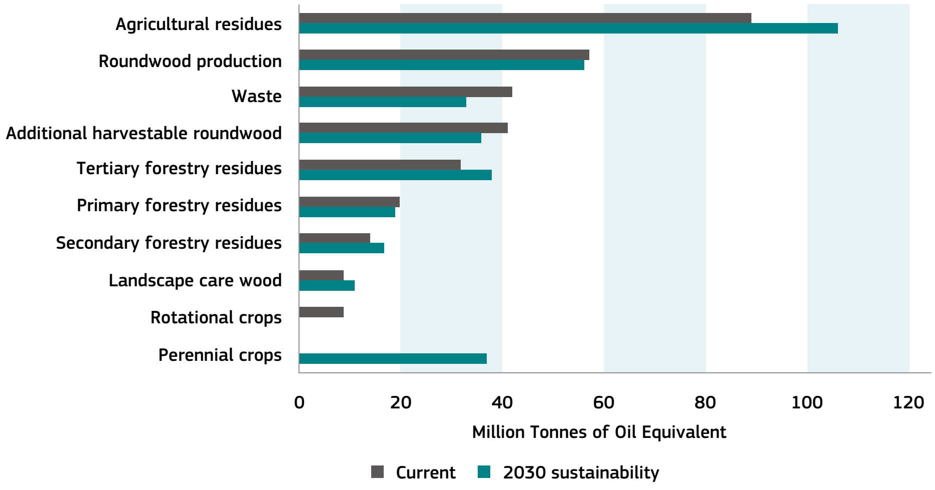
Studies on the future biomass potential reveal that the largest potential is in agricultural residues, e.g. straw and residues from permanent crops. The second largest potential is in roundwood and forest residues. Different waste streams and harvestable roundwood are considered to be third largest potential source for biomass. Figure 17 and Figure 18 summarise the estimated biomass potential trends by 2020 and 2030. The estimate

Figure 17: **Total EU Biomass potential - Current, 2020 & 2030 (Million Tonnes of Oil Equivalent)**



Source: Elbersen et al., 2012

Figure 18: **EU Biomass potential by feedstock type - Current & 2030 sustainability (MTOE)**



Source: Elbersen et al., 2012

has been carried out according to reference and sustainability scenarios. The estimate of the future potential indicates a significant increase by 2020 due to the expectation that cropping will increase on existing agricultural land and on released land with perennials crops (Elbersen et al., 2012).

The biomass market is moving towards a decentralised market for bio-based materials, biofuels and other biorefinery applications. As the feedstock availability is decentralised by nature, production of bio-based chemicals will likely also require a more decentralised structure to limit transport costs. Such decentralised processing of biomass stimulates rural development by creating new business opportunities and jobs.

Moving away from 1st-generation feedstock during a transition period, the importance of industrial symbiosis for the production of bio-based chemicals and plastics will increase. The industrial processes of different companies interact through industrial symbiosis, with companies jointly developing their activities towards a common target. The aim is to create a win-win situation for collaborating companies, giving them a competitive advantages and value, evenly generated and distributed. Economic and environmental benefits will occur simultaneously. Kalundborg in Denmark represents a well-functioning example of European industrial symbiosis (Symbiose, 2018). In Finland, the government is supporting, without forcing legislative action, voluntary agreements between the private and public sector actors to invest in smart utilisation of raw materials and side streams via industrial symbiosis (Pohjakallio, 2017).

Challenges and knowledge gaps

Due to the diverse range of bio-based feedstock in Europe, supply is fragmented and prone to variability. The main challenges lie in the locality, limited supply chain, seasonal and regional variability in availability, and volume and quality that can hamper the efficient and seamless functioning of the decentralised multi-feedstock market. According to the reviewed projects, the main challenges concerning the availability of feedstock are related to land ownership, overall demand for biomass for different end uses (e.g. food, feed, biofuel and materials), seasonal variation in availability, legislation and classification of feedstock suitability for end-use purposes. For example, around 60 % of forestland in the EU is under private ownership. The typical individual holding is small, roughly 5 hectares. Competition for wood material is increasing and the demand for industrial wood is estimated to be 2-3 billion m^3 by 2050, compared to roughly 1.7 billion m^3 nowadays (FP7 FORBIOPLAST and FP7 BUGWORKERS).

The mechanisms for a viable decentralised multi-feedstock plastic industry are currently not well understood and need to be further assessed. More knowledge and practical demonstrations of cross-value-chain operations and feedstock availability are needed. Industrial symbiosis or ecosystems are an interesting potential way of integrating local actors (SMEs, big companies, start-ups) into global networks. However, more knowledge and success stories are needed to understand the barriers as well as how assets, business models and value creation and capture models can make these ecosystems competitive. In general, what is needed is a better understanding of the potential geographic boundaries affecting cost efficiency (e.g. electricity, labour and transport costs) and decentralised supply chains (H2020 FUNGUSCHAIN and H2020 KaRMA2020). In addition, the inherent scale disadvantages of a decentralised system (at least when capital investments are involved) need to be better understood in order to create enabling conditions.

Most of the estimates of the current and future biomass potential are made from the bioenergy and biofuel point of view. There is a lack of knowledge about the current and expected share of the biomass potential for plastics and chemicals, and how the future biomass potential ties in with the estimated growth of bio-based plastics, chemicals and energy without risking food and feed production. Additionally, policy measures related to biofuels and indirect land use change (ILUC) can lead to drastic actions to avoid ILUC from lignocellulosic fuels. How this would affect the potential use of this feedstock for other bio-based products remains unclear and needs to be investigated (H2020 BIO4PRODUCTS).

The transition towards a bioeconomy puts increasing pressure on the use of arable land for applications other than food or feed production. The environmentally sound production and sourcing of renewable feedstock is a necessity as the transition towards a bioeconomy is not likely to happen with existing cropland and arable land availability. The growing demand for renewable feedstock for industrial products risks bringing about the expansion of global arable land at the expense of natural ecosystems. Currently, around 24 % of the total area in the EU is used as cropland, while studies suggest that only 15 % may be in order to achieve 'sustainable land use'. Creating more cropland by transforming forests, grasslands, wetlands and other vegetation types to agricultural land may negatively affect biodiversity, water flows and carbon, nitrogen and phosphorous cycles (FP7 TRANSBIO and FP7 SPLASH). At the same time, valorisation of marginal lands, which are not suitable for agricultural activities, through industrial crop cultivation, could provide farmers with new business opportunities and restore carbon content in the soil (H2020 FIRST2RUN).

Policy recommendations and R&I priorities

Policy recommendations

Provide information and business guidance on the opportunities and risks of bio-based products. Such information should contain the following elements: regional, national and EU level availability of biomass, understanding of biomass flows, consumption habits and sustainable aspects of the whole production chain. What is also required is an environmentally sound approach and measures for the production and sourcing of renewable feedstock for food/feed, material and energy production, including alternative renewable energy sources and crop development for marginal lands. Such transparency will also enable investors to understand the risks associated with the value chains of bio-based plastics.

Provide long-term regulatory, legal and fiscal frameworks to facilitate the development of a decentralised multi-feedstock chemical industry across Europe. Provide and implement an overarching decentralised multi-feedstock approach with clear regulatory and legal frameworks. This would strengthen and create businesses opportunities, and align local actors with global supply chains. As the valorisation of local bio-based feedstock can have significant impact on regional economics (including SMEs), such business development needs to be supported through different financial instruments and regulatory measures. In general, what is needed is a better understanding of the potential geographic boundaries affecting cost efficiency (e.g. electricity, labour and transport costs) and decentralised supply chains.

Create collaboration mechanisms to support industrial symbiosis valorising production side streams. Industrial symbiosis provides a platform for the production of bio-based plastics and chemicals. Create and implement an approach to stimulate the co-localisation of companies and clustering industries across the value chains. Develop a framework of measures that support the sharing of facilities and the use of side streams from one process for another as well as risk-sharing (H2020 KaRMA2020 and Pohjakallio, 2017).

5 BUSINESS MODELS, PRODUCT AND SERVICE DESIGN

In a wider perspective, materials – including plastics – are used to create products which serve the aims of a business model. Hence, to understand thoroughly how the plastics system works today, and how it could work in the future, one has to consider the related business models and product design:

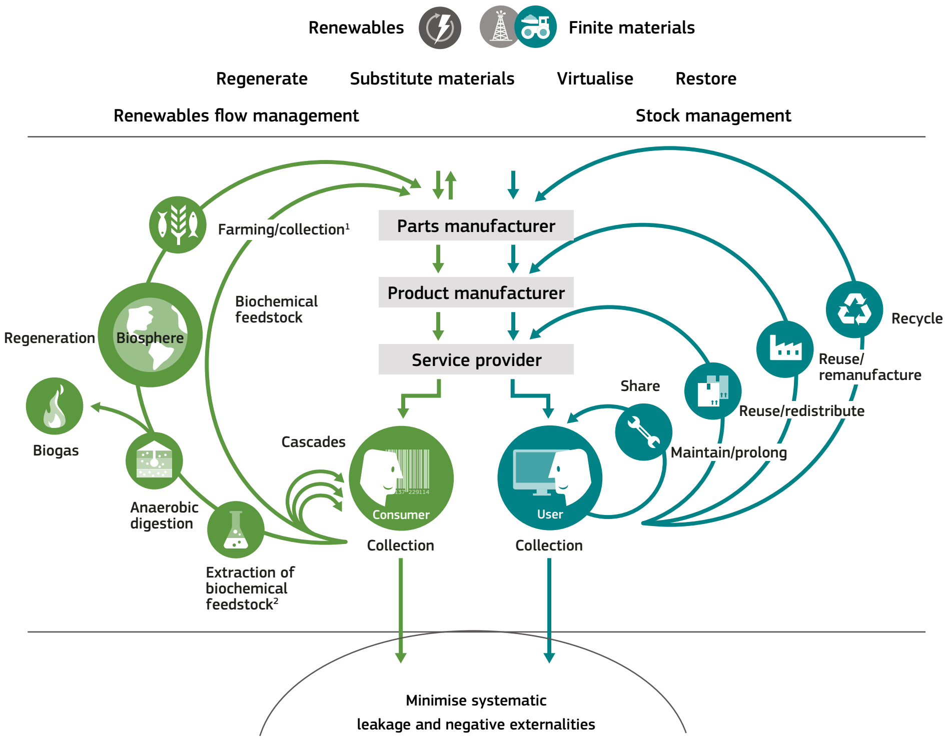
- **Business models can be defined as the rationale of how an organisation creates, delivers and captures value in economic, social, cultural or other contexts** (Osterwalder, Pigneur & Smith, 2010). There is a broadening understanding of the limitations of an extractive, linear economy, such as resource scarcity, coupled to an acceleration of technological disruptions. In this context, it becomes increasingly important to understand how the interactions between stakeholders are designed and can be redesigned more consciously. The process of business model construction and modification is also called business model innovation and forms part of the business strategy (Geissdoerfer, Savaget & Evans, 2017). This process is most relevant and effective when given a leading role within strategic design. The interactions described within a business model often define its innovative or even disruptive character. The business models of companies such as Netflix, AirBnB, InterfaceFLOR, Tony's Chocolonely, Uber and Facebook are disruptive not because of a technological advantage (which they rarely have), but because they changed a very specific interaction within an existing market, using technology as a tool rather than a goal.

- **Product design encompasses the development of products and services, covering a range of aspects that includes technical, economic (e.g. cost calculation, marketing and branding), human-centred (e.g. usability, ergonomics and aesthetics) and environmental ones.** Modern design processes typically aim to develop new products and services that are meaningful and sustainable, and enhance human interactions. All kinds of products are developed using such an integrated product development approach, ranging from consumer goods, such as toys, to industrial products, such as medical equipment.

The introduction of a circular economy framework impacts the approach to business model development and product design. As illustrated in Figure 19, a central principle is to retain products, components and materials in the economy *by design*, through several value-preserving loops, such as repairing, reusing, remanufacturing and recycling. A circular economy is often mistaken for a 'recycling economy', in which efforts are put into doing something valuable with the waste produced in conventional economic activities. However, the latter does not address the systemic issues of the linear economy (such as the creation of waste in the first place). A circular economy takes a more systemic approach to design out waste altogether (McDonough & Braungart, 2002). It includes, in general, challenging existing business models (e.g. moving from customer ownership to a product-as-a-service approach) as well as product design (e.g. durability instead of obsolescence, or modularity and ease of disassembly to enable consecutive cycles). Designing out certain materials, also known as dematerialisation, and designing for reuse or recycling are two important principles.

A circular economy pushes designers to take into account a wider spectrum of environmental, economic and social aspects of product development, which can be understood through the lens of ecodesign. While principles for 'sustainable design' have been around for over 30 years (TUDelft & UNEP, 2011), they have recently received a boost due to the increasing interest in circular economy and ecodesign guidelines. The ecodesign discipline aims to make all design considerations systemic,

Figure 19: **Schematic overview of the circular economy.**


Renewables
Finite materials
Regenerate
Substitute materials
Virtualise
Restore
Renewables flow management
Stock management
Farming/collection[1]
Parts manufacturer
Biochemical feedstock
Product manufacturer
Regeneration
Biosphere
Service provider
Recycle
Reuse/remanufacture
Share
Reuse/redistribute
Biogas
Cascades
Maintain/prolong
Anaerobic digestion
Consumer
User
Extraction of biochemical feedstock[2]
Collection
Collection
Minimise systematic leakage and negative externalities

[1] Hunting and fishing

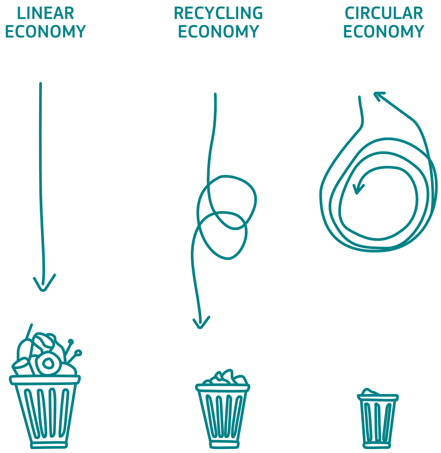
[2] Can take both post-harvest and post-consumer watse as an input

Source: Ellen MacArthur Foundation, SUN, and McKinsey Center for Business and Environment; Drawing from Braungart & McDonough, Cradle to Cradle (C2C)

including the impact of all stages of a product life – from the extraction of raw materials (e.g. oil, biomass or recycled material) to the after-use phase, and the generation of energy required along the way. The materials and energy needed are then part of production, packaging, distribution, use, maintenance, and finally reuse, repair, recycling, or disposal options. Hence, when implementing ecodesign, the designer relates all choices during the development of a product to the environmental impact for the complete life cycle of a product. By adopting such a holistic perspective on product design, ecodesign guidelines are thus aligned with the principles of a circular economy (ISO/TR 14062:2002, 2002 and Van Doorsselaer & Dubois, 2018). This close connection between ecodesign and the circular economy is also reflected in the EU action plan for the Circular Economy (European Commission, 2015b).

Since plastics often move fast through a value chain and are touched by multiple stakeholders, developing business models in line with circular economy principles requires a high level of structural collaboration. While several definitions are used, a circular business model can be characterised, combing elements of definitions from the Ellen MacArthur Foundation and the Swiss business

Figure 20: **Drawing on different economies**



Source: Plan C

theorist Alexander Osterwalder, as 'describing the rationale of how an organisation creates, delivers and captures environmental, social and economic value that is restorative and regenerative by design.' In addition, it is relevant to involve a broader group of societal stakeholders sometimes referred to as the quadruple helix, i.e. government, citizens, knowledge institutes and business. This broad range of stakeholders and the feedback-rich way in which they need to interact and collaborate make it challenging to develop truly innovative products and businesses that are favourable to circular material flows. Since plastics are often moving fast through the value chain and touched by many stakeholders, this structural collaboration becomes even more important. While innovation is often approached from a technological innovation point of view, the biggest challenge in moving towards a circular economy lies in aligning various stakeholders and changing prevailing perceptions of concepts such as ownership, information transparency, open innovation and collaboration. These challenges are more systemic and strategic by nature and are ideally addressed as such (Borgers, Versteeg, Marco Vogelzang & Bertien Broekhans, 2016).

This chapter explores how innovations in business model and product design can support a circular economy for plastics, and the key challenges to overcome. While the insights on business models can naturally be quite general from a materials perspective, the relevance to plastics is often rather direct.

5.1 Development and commercialisation of circular business models

State of play

Circular economy business models are context-dependent and are not easily transferred from one value chain to another. This dependency can be explained by looking at a business model's value proposition, delivery, creation and (partly) capture by stakeholders in different contexts (Lüdeke-Freund, Gold & Bocken, 2018). The most cited case examples are typically from outside the plastics industry and often involve sharing high-value assets to increase their utilisation (e.g. AirBnB and Uber). In contrast, plastics are mostly inexpensive materials and few automatic incentives exist to retain them inside the business or value chain. The most intuitive example is to move from single-use products in packaging to reuse models, but it creates a much more complex relationship between stakeholders. Therefore, a circular economy framework requires business to rethink the role of the physical product they bring to market and link that with its function and intention. Examples from other value chains can serve as an inspiration but care needs to be taken at the supplier-customer interface. The UK-based company Splosh is an illustrative example. Offering home-delivered household care products, they reduced the water content to a concentrate and thus drastically reduced transport costs and environmental impact. In addition, they moved the business model from single-use to reusable packaging, strengthening their customer relationships through their subscription model (splosh, sd).

From the growing number of case examples of emerging circular business models, different archetypes can be identified. Such new concepts and principles, like the sharing economy, have begun to enrich the circular economy framework by extending its scope beyond production practices to the societal level, involving citizens and radical shifts in their behaviour. These new effects of circular products, services and product-service systems require going beyond currently existing business models (Merli, Preziosi & Acampora, 2018; Bakker & den Hollander, 2014 and Chapman, 2015). The archetypes identified include (Accenture Strategy, 2014)[15]:

- **Product-service systems**, also known as product-as-a-service or pay-per-use schemes, are business models where extra services are added in order to improve and expand the possibilities for the user, or where the product in itself is transformed into a complete service. Product-service system design (value proposition) influences the interaction with the end user, which determines the economic and environmental impact of the system during and after the use phase. The service component aims to ensure a consistent value delivery through the multiple touchpoints between user and provider (Dewit). Within the context of plastics, for example, InterfaceFLOR provides an instructive example by completely servicing their carpet tiles. By adding extra services and a residual value to the product, InterfaceFLOR maintains ownership of the product, enabling it to keep the tiles from being contaminated with other materials. Both the rubber and nylon threads can be recycled, through a take-back system, which is also implemented by the carpet tiles producer DESSO (Interface and DESSO, 2008). Examples of product-service systems in packaging include the tertiary packaging and logistics in distribution chains. Another example is RePack, which offers a reusable packaging service for e-commerce (RePack). Such models rely on the end user returning the packaging, and a key challenge lies in incentivising them to do so.

- **Circular value chains** provide a more sophisticated exchange of materials between companies, so that one company's waste becomes another company's raw materials. When this occurs due to planned co-location of different industries, it is often called industrial symbiosis. The Kalundborg industrial symbiosis site in Denmark is one of the world's first well-functioning examples of industrial symbiosis and has become a textbook example of effective resource saving and cycling of materials in production in the field of industrial ecology (Kalundborg Symbiosis and Ellen MacArthur Foundation). In plastics, an example could be the co-location of sorting and reprocessing facilities with manufacturers of plastic resin and even converters. Start-ups play an increasingly important role in turning waste streams into circular value chains. Some early examples in the plastics system include Better Future Factory (Better Future Factory, sd) and ReFlow Filament (ReFlow Filament, n.d.), which turn scrap plastics into filament for 3D-printing that other companies can use to manufacture new products. Notably, w.r.yuma turns this filament into 3D-printed sunglasses with an exhaustive product-service system model, making sure that the reclaimed materials remain in the loop (w.r.yuma).

- **Product life extensions**. Often connected to product-service systems, product life extension extends the use cycle of a product by making it more durable, facilitating repair and upgrades, reuse or resell. In plastics, there are physical aspects limiting the service life of some materials (e.g. polypropylene is subject to UV-induced degradation), but this archetype could be used as a design lens to facilitate replacement of such sensitive components without having to discard an entire product. In packaging, innovators have started to experiment with moving from single-use formats to models with reusable containers for consumer goods and food service, as exemplified by MIWA, CupClub and GO Box (MIWA; CupClub and GoBox). These companies offer reusable containers that are repeatedly returned and used by a different customer, often having developed an underlying reverse logistics model.

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[15] *This summary excludes the 'Resource Recovery' (which includes recycling) business model from the original Accenture framework, as it is taken as a given in order to create a circular economy for plastics. It should further be noted that most real-life business models contain elements of more than one archetype.*

- **Sharing platforms**. Sharing platforms can come in many forms, some which are commercial and some not-for-profit. The common value-capturing mechanism is to increase the utilisation of a given product or asset (the most notorious examples include Uber and AirBnB). While for many plastics applications, such as packaging, it might not be directly possible to redesign through sharing, this archetype can be an interesting disruptor to conventional business models using packaging. For example, sharing or exchange platforms for food could be one way of designing out single-use packaging.

In a broader scope, business model development needs to be part of a bigger strategic innovation process initiated from a market need or a clear user-centred insight. Current projects are mostly technology-driven, making the technology the driving factor for the business model, rather than the other way around. A strategic innovation process goes through three phases with a clear hierarchy and reciprocal interaction. The innovation process starts at the most strategic level, understanding systemic interactions (WHY). Then this strategic vision is translated into the most relevant product or service that solves a specific need within the defined stakeholder interaction, amplifies specific behaviour or enhances the performance of the stakeholder network as a whole (HOW). The final phase brings the technological support, materials, production processes and delivery models needed to deliver this product or service (WHAT) (Sinek, 2009 and Kotler, Kartajaya & Setaiwan, 2010). At the same time, innovation can gain speed through a bottom-up approach, using the more tangible aspect (WHAT and HOW) to test the relevance of the strategic framework (WHY). A successful transition management strategy is one that manages to balance these top-down and bottom-up approaches.

Embracing complexity at the business level and in collaboration is crucial to avoiding difficulties in solving problems downstream. While most people and organisations feel uncomfortable when dealing with complexity, it is vital to remember that the simplification of a complex system will often create less relevant, technologically more challenging solutions (Satel, 2013). For example, one can consider the multi-material laminates used in plastic films. They represent a simplification to the problem of delivering food (or other products) of high quality with long shelf-lives but create technical challenges in the after-use system, as they usually cannot be sorted or recycled cost-effectively. When talking about multi-stakeholder collaboration in an environment like the circular economy, it can be valuable for governments at all levels to position themselves not as regulators and policy-makers, but as active and equal partners working to co-create and co-manage this complexity.

Digital technology, such as the Internet of Things (IoT), can play an important role when redesigning business models, but it is often not the key factor for viability. Adding sensing and communication capabilities to objects, especially fast-moving ones like packaging, increases their material complexity and possible value loss if they are destroyed, so it is vital that such technologies are used as a means rather than an end in itself. Relevant business models emerge from a user-centred approach and are supported by technological innovation. With IoT and digitisation, it becomes possible to design in more value in the use phase and in the after-use phase, which can be used to refine the business models (see also Section 5.3). By using products most people are familiar with, it is easier to test new interaction models and their supporting business models, while taking into account the costs and risks attached (Thompson C., 2018 and Richter, 2018). The rise of bike sharing in cities all around the world can be used as an instructive example. The bike in itself is a 100+ year-old invention, but with the right support of technology and data, bike sharing has become a global phenomenon at a fast pace (Richter, 2018). However, reports of recent failures in China also illustrate how sensitive the delivery model can be to external factors in society, with thousands of bikes being discarded as the underlying sharing economy business model collapsed. This emphasises the need for good design taking into account the context (Webster, 2018). MIWA and CupClub, mentioned above, are two European examples of companies incorporating digital interfaces to support their packaging reuse business models.

Investors play a crucial role in commercialising and scaling up disruptive innovations. Depending on what role they play in the investment community, from issuers of debt via venture capital to private equity and large asset managers, investors can fund new innovations and influence their portfolio companies to move towards more circular solutions. Despite this well-established fact, and although the European economy is roughly the same size as that of USA, European venture capital activity is but a fifth of that on the other side of the Atlantic (Marovac, 2017). This has implications for the possible growth and scaling of impact in innovative business models and products. As a countermeasure, the European Commission launched VentureEU, a pan-European venture programme to bring more seed and growth capital to innovative markets (European Commission, 2018p). Another reason for the often-quoted lack of capital for circular economy innovators is that the business models do not fit neatly into investors' valuation models. However, more and more investors are taking interest in the circular economy, and funds committed to investments in line with 'environmental, social and governance' (ESG) criteria are growing rapidly, currently estimated at USD 20 trillion in assets under management (Kell, 2018).

Challenges and knowledge gaps

The commercialisation and scaling up of circular economy business models still face major barriers. While the need for cross-sectoral knowledge transfer to enable systemic innovation is widely accepted, most often this is still translated into partner networks where none of the partners is directly involved in each other's business (Ostuzzi, 2017). Additionally, although start-ups can serve as an inspiration, incumbent companies find it challenging to scale up such models within their existing businesses and to make them transition drivers rather than a niche outside the core operations. If they are too different, it is hard for them to fit into the current business structure. If they are too early stage, giving them the resources to grow might prove challenging. At the same time, it is challenging to scale a business model that relies on network effects and does not reap significant advantages until the company is large enough, as this 'catch-22' effect makes initial competition with incumbents in a price-pressured market hard.

A challenge that is often brought up by companies working on the circular economy and sustainability in general is the need for a level playing field. Right now, a lot of circular economy business models focus (to some extent) on internalising costs that are considered external – for them – in the traditional linear models, such as recycling costs, and environmental and social impact. The more these external costs are covered by the stakeholder responsible (e.g. through extended producer responsibility), the more competitive circular business models will become.

New and innovative business models are hard to replicate or scale up as long as the underlying patterns in these business models are not yet clear. Even though some studies have been released discussing these patterns, the translation into business practices remains difficult (Bocken, Short, Rana & Evans, 2012 and SustainAbility, 2014). Existing knowledge is still limited, especially regarding circular economy business models. A better understanding is needed of how to scale up from a pilot and start-up phase to a more mature level of organisation and entrepreneurship in order to anchor these models within or beside the current linear model as a realistic alternative. It is crucial to extend knowledge of what innovation management and strategic business model development is, and how to use these in order to improve how companies can shift focus and strategy towards a circular economy. More specifically, three areas of knowledge need to be improved:

- Understanding of the different ways to close the loop without having to actively control or the need to know and align every stakeholder involved in the bigger value chain.
- Understanding how to develop, design and manage projects from a user point of view and deal with unknown unknowns.
- Insights into the overarching business model patterns that can be distilled from the circular business models already in place and distribution of these insights to other sectors.

Due to this general lack of knowledge and scarcity of at-scale case examples, there is still much uncertainty about which stakeholder should be responsible for what in a circular, more collaborative business model.

It remains difficult to decide which stakeholders to involve and how to ensure trust and transparency. In addition to the challenge of choosing the right partners, there is also the sensitive question of sharing knowledge and information with others. When creating business models that require several stakeholders in the value chain to cooperate, there has to be a basic level of trust and transparency. However, concerns about Intellectual Property, market positioning, and working together with direct competitors are often raised in these projects. Although patenting and IP laws were originally created to facilitate knowledge sharing and speeding up innovation, they are currently becoming increasingly decelerating (Penin & Neicu, 2018). Even though the power of collective intelligence and a multi-stakeholder approach is commonly understood as a driver of the circular economy, the reality is that there is still a big barrier to open sharing of IP and expertise, as well as a knowledge gap in what open innovation entails and how to work with it.

Since complex business models require the input of several stakeholders, the most crucial barriers are also scattered among all these stakeholders. The barriers listed below are currently considered the most important in keeping circular business models from rolling out full-scale: (Nürnberg, 2017; Bonnet et al. and Halandri, Legambiente & Zamudio, 2017)

- **Disconnect between companies' 'sustainability' aspirations and actual business models**, where significant effort is put into raising awareness of specific topics, but little is done to address the fact that increased awareness does not automatically lead to a change in purchasing decisions.
- **Legacy of low credibility**. Even when introducing a circular business model, a brand may find it hard to convince customers of their ambitions, especially when business-as-usual stays in play in parallel.
- **Increased costs**. The most circular or sustainable materials may not be the most cost-efficient from a commercial (pricing) or production (technical) point of view. Cost savings or increases may be distributed unevenly between different stakeholders, creating a tension between their ambitions, brand image and final execution.
- **Lack of financing for product owner**. Launching a circular product, especially when looking at product-service systems, requires a great amount of financial backing since more assets remain within the company. At the same time, such business models can create unfamiliar

balance sheets and not suited to conventional financial KPIs, making it difficult for the business to get the support it needs to scale up. From the financial institutes' point of view, new (risk) assessment models have to be designed, and new financial stimuli and products developed (Plan C, 2016).

When working on innovation and balancing between vision and experiment, the risk of unknown unknowns means that too much rigid planning can lead to failure. 'Unknown unknowns' are things the innovators do not yet know they do not know, and therefore cannot plan for in a rigid and fixed project (Seong Dae, 2012). Since most subsidised innovation projects call for clearly defined deliverables, timing, budgets and the expertise necessary to reach that deliverable, applicants are incentivised to make a plan for several years, defining as much as possible the next steps in a project with a strong focus and vision on innovation, especially when that innovation has to happen at a strategic level (business model level). This is contradictory to an organic innovation process, and the requested outcome of such a work package can at best define the scope, timing and budget needed to make an existing strategy tangible through a product, service or combination of both. Defining in advance the outcome, budgets, timing and expertise needed for the next steps means that innovation will not truly happen at a strategic level (although there might still be incremental innovation at the material, design and product level).

Current policy frameworks are not clear enough about the direction and measurement of the circularity of business models. A coherent policy stance on the role and direction of business models in a circular economy is often missing (e.g. regarding reuse models). Even though there are some indicators for measuring whether or not a policy is accelerating or stalling a circular economy, these indicators are mostly focused on waste management and recycling, and thus after-use products and materials (European Commission, 2018d). There is no consistent, holistic methodology for measuring the circularity of products and new business models, taking into account material usage (preferably in comparison with business-as-usual), financial risks, reuse of products, product lifetime and effectiveness. Creating a structural way of measuring circularity could provide more clarity in green deals, financial forecasting and internalising externalised costs. Local governments can help by leading by example and promoting Green Deals, Innovation Deals and circular tendering (Green Deal; European Commission and Vlaanderen Circulair), and bringing these models to local companies within their region, but such efforts are still limited in Europe.

Policy recommendations and R&I priorities

Policy recommendations

Facilitate the gathering and sharing of information on emerging business model patterns for a circular economy. By making abstract emerging business model patterns more widely available, with different use cases to support them, they can be copied and applied more easily by different organisations and sectors, shifting from industrial symbiosis to value-chain symbiosis. As a side effect, this could also help return technology to its supporting instead of leading role in business model innovation. In addition, this information could help assess the transition and monitoring progress towards circularity (European Commission, 2018m and Ellen MacArthur Foundation, 2018a).

Enable entrepreneurial opportunities in circular business models by providing targeted information and funding. Discovering the context-dependent patterns and variations of circular business models requires time and risk-taking, so direct support remains important. As is the case in many R&I domains, sharing that knowledge as broadly as possible will help make business model innovation a more tangible subject and spread successful elements. Financial support can be linked to a fund dedicated to launching start-ups that overcome the shortcomings of the current plastics system through circular business models.

Set up and maintain a collaboration platform to foster learning and knowledge exchange between business stakeholders, investors and innovators, both top-down and bottom-up. A broadened dialogue between industry stakeholders needs support, and possibly a structured framework to mitigate concerns about IP and competition issues. Projects funded with public finances could be asked to share the most relevant insights at a strategic level with a broader audience, including private investors. Learning and sharing within projects should also be more common among stakeholders from different sectors and with different expertise, with each stakeholder having a voice within the project and truly fostering co-creation and collective intelligence. Such a platform can also address fragmentation, repetition, disconnection and silos in R&I across the EU and, by extension, the world.

Incorporate testing and prototyping of business models as requirements in R&I projects to bring these strategic exercises to the forefront of R&I. For many R&I projects, the focus lies mainly on technical viability. New business models require copious testing, prototyping and gathering of feedback from the target audience, preferably if the technology is not yet fully defined. Bringing the business models more to the forefront through user- and market-testing will improve their relevance in the project and help in better scoping what materials, technologies and audiences to target.

Set up, facilitate and connect investment mechanisms that enable investors and lenders to provide funds for circular economy business models. This involves creating incentives to fund business with unconventional balance sheets or models, e.g. through discounted credits, as well as mobilising research into how to develop key performance indicators and assessment models relevant for circular business models. Other European institutions, like the European Investment Bank, should be involved in this process.

Set regulatory requirements and targets that circular business models should strive for. Once models and patterns begin to emerge, it is important to establish common ground on how to measure the impact on the circularity of these models, and what the ambitions are in terms of innovation.

R&I priorities

Develop R&I funding mechanisms that allow enough freedom to shift scope, focus and content, and communicate about these characteristics upfront. Most projects stick to the initially agreed scope, be it for the research itself, or for the narrative around it. There are good reasons to do so, especially once the hypothesis or concept has been proven. However, this can stifle innovation that could occur when confronted with new insights through the research done (i.e. unknown unknowns). Giving more flexibility in shifting focus and acting upon new insights and knowledge could help in speeding up innovation and the relevance of the projects, and in the end making these projects more outcomes-oriented and thus fully aligning the project outcome with its intention.

Take a more active role in strategically important R&I projects towards being an active stakeholder or shareholder. Governments should take a more active role in R&I projects at regional, national and European level. They should be more closely involved in setting and adjusting the R&I direction of EU-funded projects, as well as launch relevant innovation challenges with a clear vision. Such challenges should enable the project outcomes to offer guidance for policy innovation, rather than define the project's constraints too much beforehand. The active role could also be translated into taking more risks in supporting projects for the circular economy through, for example, investing in equity instead of grants. Collaboration with financial advisers with specialised knowledge of the industry in scope would be recommended, as would developing rules dealing with the high risks of public investment in circular solutions.

5.2 Development and commercialisation of circular products

State of play

As product design connects different actors in the value chain, it is crucial to successfully close material loops. Being the 'delivery vehicle' of a circular business model (Section 5.1), a product design requires that stakeholders cooperate, bring together knowledge and share the responsibility for creating a circular system. In the case of plastics, these stakeholders include polymer producers, plastics compounders, product designers, converters, brands, logistics companies, municipalities, organisations that collect and sort plastics, plastics recyclers and composting companies. As product developers can connect the different stages along the product's life cycle through the design, they plays a crucial role in this collaboration. Indeed, the designer can act as the mediator between the stakeholders by asking the right questions concerning the life cycle of the product, such as questioning whether a certain recyclable material will actually be accepted by the local recycling companies. As a result, these questions can facilitate knowledge exchange and collaboration between, for example, materials producers and recyclers (Ellen MacArthur Foundation and IDEO, 2017 and Round Table Eco Design of Plastic Packaging).

While in recent R&I projects product design is taking more of a holistic approach, it typically focuses on specific aspects of the entire system. The intent of a systemic approach can be identified, among other aspects, by cross-value-chain stakeholder involvement and the inclusion of the end-user perspective. Such an approach is witnessed in more recent R&I projects to enable the adoption of new business models, or to provide guidelines for new product design (H2020 CIRC-PACK, H2020 PolyCE and (The Netherlands Institute for Sustainable Packaging (KIDV))). Other existing examples of a more holistic approach and the implementation of ecodesign principles include Niaga®, a product design philosophy to make products healthier and fully recyclable, and SIGRE, which published the *Practical Guide to Ecodesign in Pharmaceutical Packaging* (NIAGA, 2018 and SIGRE, 2017). More generally though, R&I focuses on specific aspects of the system, with the most common categories including:

- **Improved environmental impact by choosing alternative feedstocks for producing the material used in the product.** One example is the development of bio-based alternatives to products commonly used plastics based on fossil feedstock. This could include innovation in food packaging. Similar examples can be found in non-packaging applications such as automotive and construction.

- **Improved product performance during the use phase.** The underlying idea is that better performance saves costs and resources. The most prominent example is the increasing focus on multilayer packaging, which has generated better barrier properties while using less material, but the weight reduction and barrier improvement comes at the cost of impaired recyclability (FP7 GREEN PACK). In order to improve recyclability, an increasingly studied approach is the use of mono-material packaging or of multilayers suitable for organic recycling. Examples of the former are bi-oriented stretched PP film and the recyclable 100 % PET trays for food preservation as developed by Green Pack (Valéron, 2009 and FP7 GREEN PACK). These mono-material packaging solutions might be thicker to comply with the packaging specifications, but are more suitable for cost-effective recycling. Examples of the latter include the development of compostable multilayers, since separation of the layers is not necessary if the material is composted (FP7 BIO-BOARD, FP7 SUSFOFLEX and FP7 ADCELL-PACK). Such an option can also work when using 'modified atmosphere packaging', in which the oxygen in the packaging is replaced by another gas to prolong the shelf-life of food products (FP7 BIOACTIVELAYER) In general, however, as increasingly complex product design complicates the after-use collection, sorting and reprocessing, it is questionable whether it leads to systemic benefits. With this in mind, Dutch policymakers have discussed banning metallised multilayer packaging by 2050 (Pack Online, 2017).

- **Selected focus on closing the loops in a circular economy, such as recycling or composting.** As can be witnessed in several EU-funded projects, the after-use pathways in focus are often recycling or composting, which put minimal constraints on the design and (to some degree) material choices. However, limited attention is given to other options, such as suitability for cleaning or refurbishment. Ecodesign guidelines on disassembly can help to stimulate reuse, repair and refurbishment of products and components. An example of such a holistic design approach is that of DESSO EcoBase® for carpets. EcoBase® is a polyolefin-based layer of the carpet tile designed to be recyclable in DESSO's production process. Refinity®, a separation technique enabling the yarn and other fibres to be separated from the backing, produces two main material streams that can subsequently be recycled.

To inform design choices, certain aspects of the environmental impact can be calculated with several quantitative and qualitative tools. For example, a Life Cycle Assessment study is a quantitative tool that aims to take all the stages of a product's life into account from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and recycling or disposal. However, LCA studies are often complex and the results and insights depend on the accuracy of the data, and on the time, place and interpretation. As a result, LCA results are debated regarding their accuracy or implications in the context of impact at a systems level. In addition, even when the environmental impact is studied, explanations on calculations are often generic, limited or can be interpreted in different ways, depending on the criteria chosen. The debate about multi-material films represents a good example, as they typically score well in LCAs compared to other single-use (mono-material) packaging when looking at resource use for production and energy requirements for transportation, but less so when focusing on after-use options. Reduced food waste is another aspect that would trigger good scores for multi-material films, especially from a carbon footprint perspective. At the same time, more comprehensive assessments, including (risks of) negative impacts to human or environmental health, and foregone opportunities of different business models (e.g. through reuse or short supply chains) could provide a different picture (Schweitzer et al., 2018).

Extended Producer Responsibility schemes can positively impact design for a circular economy, especially when linked to modulated fees. The OECD defines EPR as an environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle (OECD, 2016). Through an EPR system, the designer can be motivated to implement ecodesign guidelines to reduce a product's impact on the environment, for example through ensuring durability, easy disassembly or cost-effective recycling. Steering the design of products through EPR schemes has already led to economic and environmental benefits, such as lower landfill rates and higher recycling rates (Lambert J., 2012; OECD, 2016 and OECD, 2018). A study of the European Organization for Packaging and Environment found that 'EPR has been in the spotlight in recent years because it has delivered remarkable results in Europe. EPR for packaging has delivered new innovations in packaging waste management and packaging design that have reduced the environmental impact of packaging and packaged goods.' (EUROPEN, 2014). More generally, product stewardship could be seen as extending the producers' responsibility to everyone involved in the life cycle of the product. In this way, product stewardship can bring together all actors of the value chain around a specific product to take responsibility for ensuring a positive environmental and social impact. A familiar example of product stewardship is the container deposit-refund system (DRS), which is also sometimes denoted as a form EPR. A fee is paid to buy the container, e.g. bottle, on top of the price of its contents. If the container is returned, the initial fee is refunded, and the container can be reused or recycled. The latest revision of the Waste Framework Directive (Directive (EU/ 2018/851) introduced a set of general requirements for the extended producer responsibility schemes to be applied across the EU (European Commission, 2018h). One of the requirements is to ensure that whenever the producers choose to fulfil their obligation collectively via an organised Producer Responsibility Organisation, the fees paid by the producers to the system should be modulated on the basis of some criteria. These criteria include, where relevant, the products' durability, reparability, reusability, recyclability and presence of hazardous substances. The European Commission is to issue guidance on the application of this requirement to EU Member States by the end of 2019.

The shift to other business models such as product-service systems can also stimulate the implementation of ecodesign guidelines (Tukker & Tischner, 2004). In the product-service system concept, products and materials often remain the property of the companies (see Section 5.1). This ownership creates an incentive for designing the products so that they can be optimally reused, refurbished or recycled. As a well-known non-plastics example, the Philips Circular Lighting model requires users to only pay for the light, but not for the equipment (pay-per-use) as the company retains ownership. Philips offers all-in-one managed service contracts for the lighting, which involves modular components, designed for easy maintenance and replacement, and transparency on spare parts (Philips, n.d. and Ellen MacArthur Foundation). ETAP also offers 'light-as-a-service' and is, in cooperation with the University of Antwerp, redesigning products with a focus on disassembly, reuse of components and recyclability of the materials (Etap Lighting, 2018). Schoeller Allibert, a manufacturer of plastic returnable transit packaging, has optimised the design of its reusable crates to facilitate optimal handling and reuse, to the benefit of its customer base of pool operators (Schoeller Allibert).

Product design influences the interaction with the end user, which determines the impact during use and the ability to close the material loop. Common examples of the design-usage relationship include the use of energy and the use and disposal of products, such as single-use coffee cups. Whether the products will be effectively reused, recycled or composted depends to a large extent on decisions made by the end user. Behavioural insights and guidelines can support design that guides the user and makes it easier to close material loops and prevent leakage (Lidman & Renström, 2011 and Coskun, Zimmerman & Erbug, 2015). In addition, the user can be informed of both the opportunities and obstacles to cycling the product in a value-preserving way through what is communicated by the design. In line with the revised Packaging and Packaging Waste Directive, the European Commission is reviewing essential requirements for packaging, affecting the product design (European Commission, 2018i).

Challenges or Knowledge Gaps

By focusing on a limited set of aspects, product design is missing full life-cycle thinking, crucial for the transition towards a circular economy. While several examples of ecodesign thinking exist for packaging, their limited focus, such as on feedstock replacement or improved performance, can lead to unintended consequences. For example, when shifting to a different feedstock, which often equals a complete material replacement, limited attention is given to after-use reprocessing in practice, even though this could lead to disrupting that part of the system. Similarly, the strong commercial trend to use thin, multilayer packaging to reduce material and improve performance hinders recycling as it is difficult and costly to separate the layers, and recycling a mix of plastics typically results in lower quality recycled materials. In addition, the role of design in enabling collaboration across the value chain is not fully explored.

Product design that takes into account after-use pathways, such as recycling and composting, does not often consider local practices and infrastructure. There is often no link between the designers' intent and the recycling or composting strategy in several Member States. For example, some R&I projects investigate different after-use pathways of new bio-based plastic packaging solutions, but there is no connection with the composting possibilities in practice. As such, there is no guarantee that the products will be recycled or composted. For recycling, the product developer can be stimulated to use recyclable plastic compounds, but whether the products and components are really recycled depends on the logistics and infrastructure for recycling. Where there are no opportunities to recycle, as is still the case in multiple regions in the EU, it does not matter how well the packaging is designed. Similarly for composting, in Flanders only certified compostable bags are allowed for collection with organic waste, and all other compostable packaging and products are forbidden. The main reason for this prohibition is to avoid contamination of the organic waste stream with non-compostable items.

In general, high product complexity hinders recycling. While sorting and recycling processes and technologies have improved in the past years (see Chapters 7 and 8), increasing product complexity continues to generate costs and reduce the quality of recycled materials. Such complexity is, for example, expressed through the types of materials, compounds, adhesives, pigments and other additives used in the product. In the case of multiple materials, a suggested approach is to add compatibilisers to the recyclate to make different polymers mix better into a homogenous matrix, and thus improve the material properties. However, the compatibilised blend can complicate further recycling and can cause additional contamination, including with hazardous substances. Rather than looking for end-of-pipe answers, the recycling problems can be anticipated and tackled at the start of the life cycle through design choices. The designer can rethink the product using ecodesign principles. However, methodologies to evaluate the environmental impact of such a systemic approach are currently not well developed or transparent.

Product design is sometimes misused for making green claims, adding to the existing confusion. Some companies introduce their product to the market claiming it is environmental friendly, although under closer scrutiny it does not add systemic benefits. For example, while a hair dye packaging tube was initially made of 100% aluminium and fully recyclable, after redesign, the tube was made of a PE/aluminium/PE multilayer which cannot be recycled. Nevertheless, the design won a green packaging award due to its lightweighting. More broadly, labels like 'compostable' or 'recyclable' are commonly mentioned on products even if there is no organised system in place to collect and mechanically/organically recycle. While strictly speaking this is not wrong, such practices increase existing confusion or misinformation on how products are dealt with after use.

There is no universal method for assessing products, including packaging, for their alignment with circular economy principles. The steps of an LCA study are standardised in the ISO 1404X norm, but several aspects, including the system boundaries, assumptions and weighting factors, are not restricted, which casts doubt on the conclusions of different LCA studies that compare different solutions. In particular, the term 'recyclable' is used quite often, but should go beyond technical recyclability to be meaningful from an impact point of view. Following up on the EU Plastics Strategy, the Joint Research Centre is working on LCAs for plastics made from different feedstock materials (Joint Research Centre, European Commission, 2018).

Policy Recommendations and R&I priorities

Policy recommendations

Develop and implement EPR systems with modulated fees to steer product design towards circular pathways. Such design would include the use of mono-materials or cost-effective separation of composites/multi-materials, and business models based on reuse and repair. The latest revision of the Waste Framework Directive (Directive (EU) 2018/851) mandates the use of eco-modulation of fees for the existing and new EPR schemes based on several criteria, including recyclability (European Commission, 2018h).

Set regulatory requirements for plastic products to contain a minimum level of recycled content, in combination with requirements on safety and technical performance. Promote the market for recycled materials through setting clear criteria related to recycled content for different product types. The EU-wide pledging campaign for the uptake of recycled plastics, as announced in Annex III to the EU Plastics Strategy, is an example of such an effort (European Commission, 2018j). Product selection and target setting should ensure that human and environmental health are not jeopardised (e.g. through food contact materials or hazardous substances), and that skewed incentives are not created (e.g. resulting in products which are substantially more difficult to recycle). It is important to note that users of recycled plastics may actually be subject to waste legislation, including possibly needing a waste treatment permit if handling or processing recycled plastics.

Set up product policies and standards that simplify the products landscape, balancing economic, environmental and social impact, by taking an outcomes-oriented approach. As with the case of single-use plastic products for certain applications, one can think about the disincentivising non-recyclable multilayers and products that are produced out of inseparable plastic components. Recycling can be promoted, for example, by stimulating mono-materials for selected product groups, e.g. toothbrushes which are currently a mix of PP, TPE and PA that is not possible to separate. Composting can be promoted by creating standards for selected product categories, e.g. tea bags. Standardisation of the plastic compound for some products can be an option for achieving this need. For example, a fixed grade of acrylonitrile butadiene styrene (ABS) together with a certain amount of standard additives could be used for the housing of electronic devices, or a selected polymer with a chosen set of additives could be used for selected food packaging applications. Such standardisation could generate high-quality recycled materials, which is crucial for creating a virtuous circle of higher recycling rates and higher-quality materials.

Develop a universal evaluation methodology resulting in design guidelines and/or standard circularity metrics to evaluate the circular economy potential of products and services. Current LCA methodologies are insufficiently adapted to the systemic approach of a circular economy (Schweitzer, Petsinaris & Gionfra, 2018). In addition, there is discussion about the accuracy of the results generated with an LCA, including their dependency on time, place, data and interpretation. A universal evaluation methodology should bridge these shortcomings by including more systemic elements, grounded in local reality (e.g. impact of one product on other material streams, or the likelihood of recyclable products being recycled). Inspiration could be drawn from qualitative tools based on guidelines, such as the LiDS wheel. One aspect of this methodology would be the development of harmonised definitions. For example, 'recyclability' should take into account whether the item, when put on the market, is collected for recycling, has market value and/or is supported by a legislatively mandated programme to ensure it is sorted, recycled and made available as secondary material (Plastics Recyclers Europe; The Association of Plastic Recyclers, 2018).

R&I priorities

Incorporate a demand for a holistic, circular approach when developing funding requirements. Such an approach is reflected in different ways, including value-chain collaboration, understanding of likely after-use pathways and consideration of environmental and social impacts beyond the use phase. Cooperation cross the value chain is essential for gaining a systemic overview of the life cycle of a product. Knowledge of after-use option helps to get a complete insight into the total environmental footprint and pathways to close the circle. A broader approach should incorporate the impact of the entire life cycle of the (plastic) products on human and environmental health. The outcome of innovation taking a holistic perspective should be a thorough reflection on the relevance and shelf-life of the proposed conclusions. While such an approach could mean less control over the projects, it potentially provides a much higher pay-off in the long term.

Provide funding to drive R&I in specific design areas, including citizen behaviour and collection, disassembly and separation, and mechanical, chemical and organic recycling. Such targeted R&I would foster a better understanding of the role design plays in a circular economy framework. Citizen behaviour and collection is one area of interest. A crucial stakeholder in closing the loop is the end user. While products can be designed for recycling, with logistics and recycling programmes in place, neither of these is enough if it is still not straightforward for the end user to dispose of the item in the intended way. User-centred design can help overcome such barriers, for example, through active measures such as informing the user where to put the product, or passive ones, such as an opening in the collection bin that only permits a certain format. Incentives can also be financial, as with deposit-refund schemes. At this point, however, little is known about which incentives work well and in what context, prompting further research. Disassembly and separation is another area of importance. Designing plastic products, especially items that require more than one material, for easy disassembly or separation is crucial for closing the product, component or material loop. Mechanical, chemical and organic recycling is a third area for design focus. Designers need a better understanding of what makes (plastic) items easy to recycle, and what material choices are available for different recycling pathways. See Part III of this report for a more thorough discussion of the after-use system.

5.3 Information transparency and its implications for design

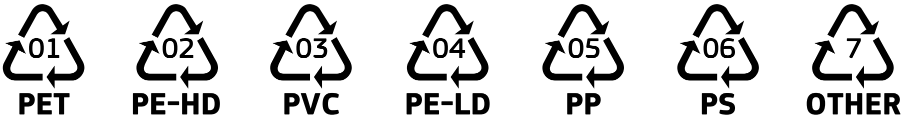
State of play

Information is valuable as it, for example, creates the distinction between a heap of undefined waste and a pile of valuable materials. Asset tracking, i.e. information on an asset's location, condition and availability, is a central enabler of circular business models and material flows (Ellen MacArthur Foundation, 2016a). In plastics, three key reasons can be given for increasing information transparency:

- To monitor and improve logistics and (packaging) performance (e.g. by logging time spent in different environments).
- To make reuse, sorting and recycling more effective (e.g. by tagging individual items to enable identification).
- To ensure health and safety for users during different life cycles (e.g. by sensing microbial activity).

In each of these cases, two abilities are necessary to add value to the system: the ability to record and/or communicate data (monitoring or tracing), and the ability to make that data available to relevant stakeholders (information transparency). While benefits could be reaped broadly across value chains and sectors, implementation of such abilities remains challenging, driven by the implications new technologies have on product and business model design, potential clashes with the intellectual property system, and the necessity of creating some kind of standardisation for information transparency.

Figure 21: The ASTM International Resin Identification Coding System



Source: Wikipedia, CC0 1.0 Universal

In plastic packaging, information transparency is currently almost non-existent. As discussed in Chapter 3, competition drives differentiation of materials. Because the competitive advantage lies in the specific formulation of that material, there is no incentive from the producer side to share anything but basic or legally mandatory information. The little material information on plastics items in the form of the ASTM International Resin Identification Coding System is not effective, since it only indicates the (major) types of plastic and not additives or fillers (see Figure 21). In addition, the system has evolved towards ever-increasing diversity and complexity, making information difficult to process even if available. Any approach to increase information transparency would have to address these basic challenges.

Several established technologies or approaches exist to provide traceability and information transparency, all of which are still in early pilot stages in plastics. Creating information transparency about material composition is challenging, due to the fast-moving nature of plastics through the value chain (especially in packaging) and the relatively low material value of individual items. The methods that do exist to identify plastics (see Chapters 6 and 7) are mainly reactive and cannot handle most of the material variations and complexity present on the market. There are, however, several approaches for which the technology is already mature, and that are discussed as possible solutions.

- **Electronic tagging**. Technologies such as radio-frequency identification (RFID) tagging are already in place in applications such as logistics, where they are used to track containers and other large tertiary or quaternary packaging items. In packaging for food service, they are likely best suited to enable systems for reusable items and business models built on reuse. The start-up CupClub is one example, where RFID tags are placed on returnable coffee cups to enable a decentralised deposit-return system with a digital interface (CupClub).

- **Chemical tracers and digital markers**. To improve on the shortcomings in current spectroscopic technologies for sorting plastics, which for example cannot identify black or some other opaque plastic items, embedding a machine-readable tracer or marker has been proposed (FP7 POLYMARK). The multi-stakeholder PRISM project, led by the company Nextek, has developed a series of UV-fluorescent chemical markers designed to overcome this problem. The project, which concluded in 2018, showed 90-98 % yield with 95-99 % purity at industry-level conveying rates (Nextek, 2018). Similar technologies include Polymark, ErgisMark and Polysecure (FP7 POLYMARK, (ErgisMark) and (POLYSECURE)). A chemical tracer acts as a binary 'code' as it is either present or not. In principle, it is possible to combine several tracer molecules with unique spectra to increase the number of possible codes. For example, four different molecules would enable 2^4 = 16 unique codes. However, the amount of specific polymer grades and combination with additives means that the potential for higher code resolution is large. Digital watermarks are optical tags the size of a few pixels, which can be embedded in artwork or embossed in the mould of an item. The technology has recently generated increasing interest in the plastic packaging value chain. Project HolyGrail, run by a consortium led by P&G within the New Plastics Economy initiative, is investigating how digital watermarks could be implemented in packaging to improve sorting (P&G, 2017 and Ellen MacArthur Foundation). The interest in the technology comes from its simplicity and potential flexibility:

- The number of available codes is large and can be increased over time; as such, it does not rely on significant technological innovation to be upgraded.
- The identification of a digital watermark can be done with a suitable (high-speed) camera and the appropriate software.
- It is a non-invasive way to embed information in any packaging item, where an identifier could for example be paired with a material passport (see below). With a suitable standard it enables, in principle, tracing items back to individual retail locations, manufacturing plants or even batches. This would provide a technological basis for accurate tracking of material flows and valuable feedback on what share of different plastic items actually makes it back to recycling.
- Since the watermark can be read by a digital camera, it enables a new user interface, including augmented reality. Marketing opportunities aside, it can also be used to convey guidelines about how to recycle the item.
- The digital watermarks are compatible with the GS1 standardisation and can be used instead of standard barcodes or QR codes (The Wall Street Journal, 2016).

- **Material passports**. Another stimulus for improving the after-use processing of materials is the introduction of a (digital) material passport for the product, sometimes called a 'nutrient certificate'. Material passports are datasets that describe material characteristics in products (e.g. precise information on polymer type, grade and additives), sometimes along with details on composition and assembly, which give them added value in the after-use phase. The certificates can be seen as a marketplace mechanism to encourage product designs, material recovery systems, and chain of possession partnerships that improve the quality, value, and security of supply for materials, so they can be reused, recycled or safely returned to biological systems (Hansen, 2012). Material passports have initially been introduced for high-value assets with long use cycles, such as ships or buildings, in line with the concept of 'Buildings As Material Banks' (Ellen MacArthur Foundation; BAM, 2017 and BAMB). In plastics, they can be seen as applicable to durable goods, or to packaging if tied to a tracer or marker system (see above). Such passports could in principle be traded as a derivative, since they are based on an underlying asset with a real value, unlocking new financing solutions, e.g. for a start-up company. Developing a standardised passport could also address inherent 'unknown unknowns', since it can inform a future, yet to be identified, stakeholder or process about what materials they are dealing with. Based on the revised Waste Framework Directive, ECHA is currently working on a database on the presence of hazardous chemicals in articles for waste treatment operators and consumers (ECHA, 2018c)

- **Standardised materials**. Another approach to creating information transparency is to standardise which materials are being used for a given application, eliminating confusion or uncertainty. Using a standardised list of materials, for example for housing of certain electronic devices, could reduce complexity and increase yield and quality in the after-use system, reinforcing circular material flows by providing higher-quality recovered materials.

Information transparency increases the potential for open innovation and investments. In some cases, open innovation can be a highly efficient way of generating new business model or technology innovations. Since it relies to a large extent on open access to data, increased data transparency could significantly boost open innovation activities (European Commission, 2016a and OECD, n.d.). Investors require consistent data to assess and compare different investment opportunities. In addition to financial data, this increasingly needs to include social and environmental information to identify and understand good practice for supporting the transition to a circular economy. Transparency also allows them to understand the risks associated with the supply chain.

Challenges and knowledge gaps

There is no consensus on what data is needed to provide the information necessary to effectively close the plastics material loops, and on how to best manage it. Some indicators have been defined, agreeing on how to measure circularity (European Commission, 2018d). However, the type of data needed, the actors responsible for capturing it, the means and time points for data collecting still remain a challenge. A related question concerns who should own and manage the data once it is generated, e.g. a private independent operator or a regulatory body.

It is not yet clear which technological solution would best suit what system, and how to best standardise such technology. While technologies to generate more transparency are mature, their implementation in plastics value chains are not, and there is uncertainty about how to create meaningful standards. Multiple stakeholders would need to make significant investments into assets and R&I to implement a given solution across the value chain, but the direct return on that investment would be relatively unclear. Furthermore, if such standards impact different stakeholders unsymmetrically, there is a risk that resistance to implementation will be large even if the benefits to the system are apparent.

Industry is typically not comfortable with information and data sharing. In the absence of any realigned incentives, it is unlikely that individual stakeholders will see a benefit in releasing information that is a basic part of their business. Since it is not clear what data will be requested (and to what level of detail) for what purposes, it is difficult to conduct productive discussions between stakeholders and regulators. In addition, there are legal concerns about privacy and IP, e.g. data collection during the use phase (General Data Protection Regulation). Another challenge is the balance between governments and markets driving the creation of a data transparency system. Ideally both sides would agree on a set of specifications and level of openness, but it is likely that there will be a debate where some stakeholders have opposing interests that are challenging to reconcile.

There are potential unintended consequences of tracing or signalling equipment. In general, including a tracer, sensor or communicating device adds complexity to the product, which can make the after-use processing more complicated and expensive. As such, improving traceability and information transparency could be counterproductive if the goal is to close material loops. Care must therefore be taken to avoid such unintended consequences.

Open innovation brings challenges in trust and critical mass. Open access to information does not guarantee thriving open innovation. Although it is a frequently used term, it is seldom implemented in corporations. And even when it is implemented, it is often limited and in partnerships with companies that are not direct competitors. In a circular economy however, stakeholders within similar markets, product categories, materials or technologies should feel safe enough to collaborate with each other in order to improve material loops. Should an open innovation system reach a (for the circular economy still undefined) specific threshold scale, clear policy regulations have to be put in place to avoid unintended consequences. At the same time, this creates a certain tension as such regulations might automatically limit the possibilities of further open innovation.

Policy recommendations and R&I priorities

Policy recommendations

Strengthen existing or develop new regulatory and legal framework to address privacy, competitiveness and IP protection issues when enabling data collection and sharing through digital platforms. A successful platform for data transparency may need mechanisms to protect IP and other sensitive information. Such mechanisms should also protect citizens' privacy in line with the General Data Protection Regulation (GDPR). Use of new decentralised technologies, such as blockchain, could be a way to ensure this, but the opportunity needs to be thoroughly investigated.

Develop and provide business guidance to ensure that tracing or signalling equipment does not negatively impact the after-use system. Certain types of technologies may be ill-suited for specific applications and formulating guidelines (and possibly also incentives) to help the market avoid those could mitigate unintended consequences.

Facilitate collaboration to ensure a greater level of openness between market players through data-driven open innovation. By opening up the data collected, individual industrial symbiosis networks can become more resilient through interlinkage with each other, and new players can more easily join these networks. By opening access to such data, industrial symbiosis could also extend beyond the production industries where it is currently most common.

R&I priorities

Provide funding for research to understand what data is needed and how it should be managed. Greater insight is needed into what datasets should be made open and to whom. Data transparency policy should be clear on the extent to which data can be shared with both competitors and the public.

Provide funding to develop technologies for creating information transparency, while fostering a discussion on how to create industry-wide standards. More exploration is needed to investigate which technologies are suitable in different systems (e.g. chemical tracers, digital markers, material passports, optical recognition with artificial intelligence). An open discussion on how to use and standardise any such technology is necessary, and policymakers are well placed to facilitate them.

5.4 Societal and technological trends impacting plastics design

State of play

Several trends are increasingly defining the success of circular economy business models and product design for plastics, and beyond. These trends can be of societal or technological nature, or a mix, including:

- **Increasing complexity and interconnectedness** of stakeholder relations, making it insufficient to focus a business model primarily on a quality versus price dimension. Even though most trend forecasting is being conducted from a technical point of view (e.g. Gartner Hype Cycle), big disruptions will also include societal changes. Frameworks such as the planetary boundaries, UN Sustainable Development Goals, and the doughnut economy give additional insights into how, why and in which directions the systems are shifting (Steffen et al., 2015 and Raworth, 2013-2018).

- **New ways of collaborating across organisations.** The increase in complexity calls for new ways of gathering and applying knowledge and insights. Open innovation and collective intelligence are key in this context (European Commission, 2016b).

- **Increasing interest in information transparency** for all stakeholders (see Section 5.3). For the circular economy this is true for both the production and innovation side, but also when building brand image and credibility in relation to end users and NGOs.

- **Increasing possibilities from new technologies**, such as decentralised production (with 3D printing as the best-known example), marketing-driven technology such as personalisation, smart sensors on packaging, and after-use innovations such as digital or chemical markers, and chemical recycling (see Chapter 8). Another trend, fuelled by connected devices like in the Internet of Things, is the usage of data to create a more closed system in terms of material leakage, but more open in terms of data and transparency. Such new technologies can offer significant benefits, such as customised packaging, product quality control, and improved packaging information. Digital material passports could enable higher transparency and value of the constituent materials after the use phase (see Section 5.3).

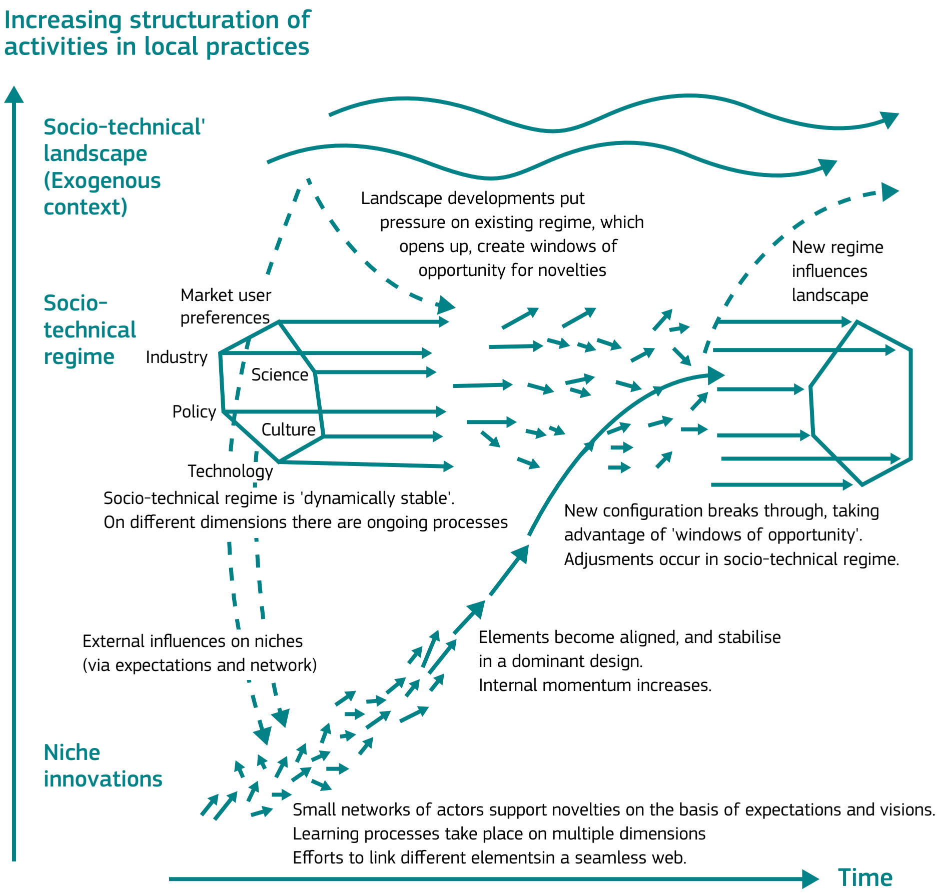
- **Public awareness of plastic pollution and demand for action.** The rising awareness about the unintended consequences of plastics has triggered action globally from policymakers, NGOs and businesses. While it is unclear to what extent this recognition influences actual purchasing decisions, it has already stimulated designers and producers of plastic products to implement the principles of ecodesign and the circular economy.

These trends create opportunities to transition niche ideas towards a mainstream breakthrough. As illustrated by the socio-technical landscape map outlining transition dynamics (Figure 22), moving innovations from niche towards mainstream is enabled by socially-induced pressure on the current technical regime. The moment innovations reach a wider breakthrough, they will start impacting the socio-technical regime themselves, i.e. they hit a tipping point and structurally impact behaviour and policy. This subsequently leads to a virtuous circle of positive disruption. Setting up successful transition experiments is about finding the right balance between translating big societal trends and developments in a niche innovation that focuses on changing a specific behaviour or habit (Thompson C., 2018). For example, in delivery models the impact of decentralised production and personalisation could be game-changing if translated correctly using the right product for the right target audience. The moment developments in the socio-technical landscape, for example the call for more transparency, are connected with new technological innovations, e.g. use of chemical markers in plastics, within a new business or behaviour model, there are fewer 'unknown unknowns' (see Section 5.1).

Successful circular business models have shown responses to these trends and opportunities. In the plastics sector, we already see these trends at play in several companies: w.r.yuma uses a new technology, i.e. 3D printers in this case, and recycled dashboards to create sunglasses (w.r.yuma); Patagonia provides information transparency by sharing the recipe for their seaweed-derived wetsuit material with their competitors to enhance the impact, and their credibility (Patagonia); Interface is acting on new technological opportunities and on rising awareness by using fishing nets as new feedstock in their product-service system model (Interface) and Ecovative is using mushroom material as a replacement for traditional packaging and insulation materials, tapping into a large open science community for their innovations (Ecovative).

New technological opportunities and business models impact packaging design. If business models change such that the product specifications are altered (e.g. need for more durability), they inevitably impact product design as well. Designers may have to invest in exploring new best practices, as conventional wisdom is challenged. In parallel, more tools and technologies are made available. Specifically, making packaging interact with its surroundings by using different forms of embedded information, microelectronics and nanotechnology, creates new opportunities but it also presents new challenges.

Figure 22: **Socio-technical landscape map over transitions**


Increasing structuration of activities in local practices
Socio-technical' landscape (Exogenous context)
Socio-technical regime
Niche innovations
Landscape developments put pressure on existing regime, which opens up, create windows of opportunity for novelties
New regime influences landscape
Market user preferences
Industry
Science
Policy
Culture
Technology
Socio-technical regime is 'dynamically stable'. On different dimensions there are ongoing processes
New configuration breaks through, taking advantage of 'windows of opportunity'. Adjusments occur in socio-technical regime.
External influences on niches (via expectations and network)
Elements become aligned, and stabilise in a dominant design. Internal momentum increases.
Small networks of actors support novelties on the basis of expectations and visions. Learning processes take place on multiple dimensions Efforts to link different elementsin a seamless web.
Time

Source: Geels, 2011

Several different terminologies are used to describe such packaging, including active packaging, intelligent packaging and smart packaging, most often referring to packaging systems used for foods, pharmaceuticals and several other types of products (Kerry, 2008). Active packaging means having active functions beyond the passive containment and protection of the product. Smart packaging involves the ability to measure the quality of the product, the inner atmosphere of the package or the shipping environment (Packaging Europe, sd). This information can be communicated to suppliers or users, or trigger active packaging functions. These technologies help extend shelf-life of the packaged product, monitor freshness, display information on quality, improve safety and improve convenience. However, adding functionality to fast-moving products also comes with the challenge of increased material complexity. Several of the above-mentioned technologies are being studied in EU-funded projects, e.g. oxygen scavengers, which hinder recycling, were added to prolong shelf-life (FP7 BIOACTIVELAYER), antioxidant and antimicrobial compounds from residual orange peels were incorporated into packaging and edible coatings (FP7 SUSFOFLEX) and an antimicrobial coating was added that reduced the required amount of directly added preservative to the food (FP7 FLEXPAKRENEW). Often the challenge remains how to make such technology fit into the wider system.

There are strong ongoing societal trends that drive the status quo in plastics and packaging. For example, an increasingly mobile ('on the go') lifestyle that places high value on convenience has driven the proliferation of ready-made food in single-use packaging, a trend that is expected to continue with the growth of a global middle class (European Commission, 2018b). With the current growth of e-commerce, there is also a visible increase in the demand for packaging solutions, such as light packaging to reduce shipment costs. Solutions for closing the loop of the packaging used for e-commerce will gain significant importance. As shown by RePack, a reusable and returnable packaging service can be such a successful solution (RePack).

Pay-As-You-Throw is a policymaking approach that can nudge behaviour towards a circular economy. In this approach the polluters pay based on the amount of material they throw away. This model is often used by local governments in municipalities to nudge people into better sorting, making it easier for recyclers to process waste streams. A good example of a successfully implemented pay-as-you-throw model are the 50 municipalities of the Priula Consortium in Italy, which had a separate collection rate of 85.1 % in 2016 and aim to achieve 96.7 % by 2022 (H2020 WASTE4THINK). In Belgium, a pilot project is being conducted where citizens can buy new and cheaper rubbish bags exclusively for products made out of (non-PET bottle) plastics. The first results show a big reduction in the volume of materials that had to be sent to energy recovery because it could not be separated enough for qualitative recycling.

Challenges and knowledge gaps

There is a lack of understanding of how to deal with unknown unknowns inherent to new trends. A big challenge lies in embracing the uncertainty inherent in the future, and learning how to deal with unknown unknowns. New insights to deal with this uncertainty could be generated by linking typically rather distant domains, such as more theoretical transition management with more hands-on design thinking, or traditional for-profit business and social entrepreneurship. The work conducted at places such as the Stanford Center for Social Innovation, or publications such as *The Art of Revolution*' and '*The Way to Design* can provide inspiration (Stanford Graduate School of Business; Fields and Vassallo). These methodologies have a direct impact on the strategic business model and therefore on the products and services designed, without forcing a specific material or technological focus.

There is a limited understanding of the potential of decentralised production in the circular economy. Such insights are needed to better understand the role of the 'long tail' economy and local production in it, as explored for example by w.r.yuma and Open Desk (Anderson, 2006; w.r.yuma and Open Desk). Closely tied to this challenge is understanding to what extent designers and engineers are designing based on what they know instead of what they need. Digital production technologies offer a freedom of form not seen before in industrial production, but this trend has not yet achieved much momentum.

Innovation methodologies typically do not incorporate enough iterations or a systems-level scope to adapt to evolving societal trends. When an innovation project is managed through a design process instead of the traditional management processes, one of the big challenges is to reflect on the outcome of each iteration by looking not only at what was done, but also why. Iterative learning, including trial-and-error, needs to be combined with simultaneously taking time to reflect what factors in the process shaped the outcome, such as assumptions and biases that defined the outcome, or stakeholder roles in the project. Taking a conventional, less iterative approach to innovation leads to fewer opportunities to consider, and design for, all the steps of the product life cycle, or results in missing other key systemic outcomes.

For example, new technologies such as microchips, sensors and other electronics could significantly impact recycling processes unless the after-use system is designed to adapt to the added complexity. Similarly, 3D printing of plastic products could lead to extra scrap material if the design process does not address this properly.

There is a risk that use of single-use packaging trumps other societal trends. Increased awareness aside, convenience and cost sensitivity are strong drivers of purchasing decisions, and despite an expanding menu of design and business model options, it is not unlikely that the status quo will prevail. In addition, while new technologies offer new benefits, concerns about human health and environmental impact are often raised against them. Hence, it is evident that new technologies alone are unlikely to disrupt the current system. EU-funded projects have also mentioned the delicate issue of using 'non-conventional' technology (such as nanomaterials and recycled plastics) in food and other sensitive applications due to health-related concerns. In such cases, innovators rather hold off going to market before gaining a better understanding of potential impacts (FP7 FLEXPAKRENEW and FP7 SUSFOFLEX). This situation illustrates both how challenging it is to disrupt the current system with new technology, and that technology innovation without a broader systemic approach runs the risk of developing an innovation without a feasible application.

Policy recommendations and R&I priorities

Policy recommendations

Provide financial incentives for innovation that uses digital technologies, such as AI, IoT and blockchain, to improve product or business model design for a circular economy. Such technologies and mechanism could predict future or generate actual information on different aspects informing the design process, including a product's location, condition and availability, or user interaction. For example, smart devices and sensors could provide information on the use and disposal of products, which could feed into design processes to improve its durability and the ability to repair, collect and recycle. Plastic packaging or other products can be connected to consumers through an app or digital platform, creating opportunities for new business models. Other examples include the use of AI for designing new products that enhance user interaction and reduce complexity or material need, and the use of digital twinning, which is the mapping of a physical asset to a digital platform.

Facilitate the gathering and sharing of information on behavioural economics, and the impact of policy on known patterns, both at local and European level. Since one of the greatest challenges in the transition towards a circular economy lies in customer and citizen decision-making, the topic needs to be explored in much more depth, and insights shared with entrepreneurs and organisations working on the circular economy. The role of innovative policymaking, including nudging and different types of taxation, should be explored too.

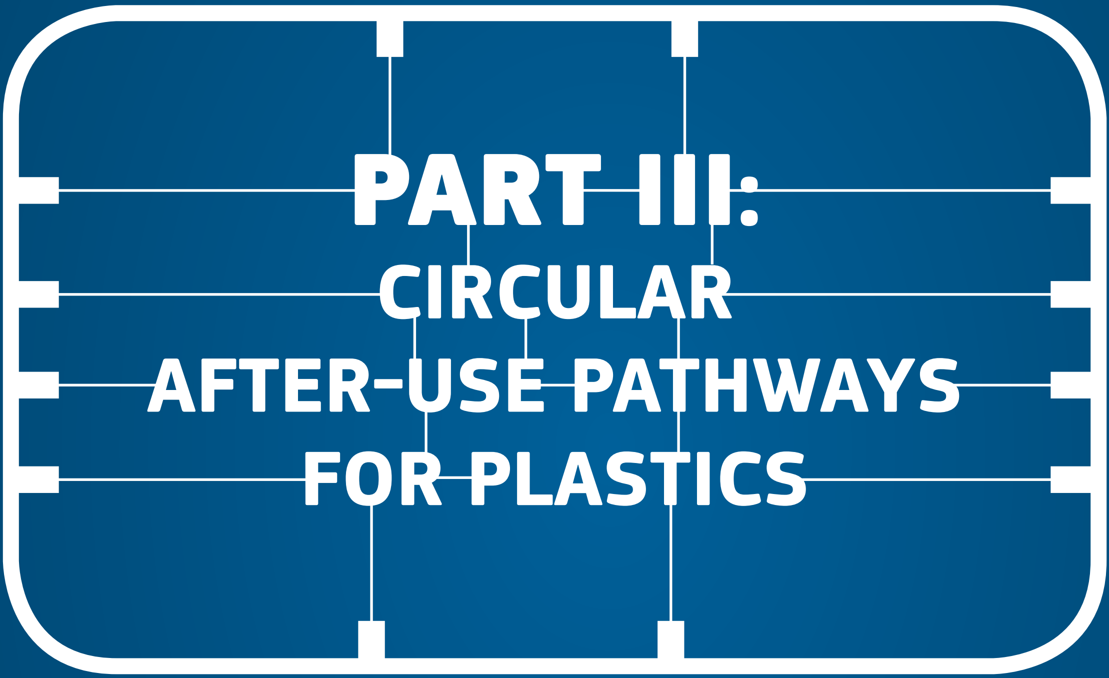
Develop regulatory frameworks for ecodesign going beyond energy and resource efficiency. Addressing a certain need in society by designing a business model, product or material, typically takes into account more than only energy or resource efficiency. Hence, ecodesign frameworks should reflect this by including other aspects of the life cycle, including durability, chemical safety and social value (European Parliamentary Research Service, 2017).

R&I priorities

Provide funding for research to understand the potential and success drivers of business models using decentralised production. Such research should generate insights into three key areas: technical and business insights, such as cost efficiency and resource productivity; insights into how such technologies interact with and are received by customers; and insights into how decentralised production can fit into a circular economy without unintended consequences, such as additional scrap material generation.

Incorporate mechanisms to create the right context before shaping the content, in R&I funding criteria. For transitioning complex systems, creating the right enabling conditions for change is often the most difficult part. Through R&I funding criteria, policymakers can outline such a context both at a project and a system level, once knowledge and patterns become repeatable. Once the context is clear, more concrete and detailed insights, ideas and specifications, e.g. financial aspects, technologies and material choice, can be included.

Provide funding for research to understand the potential and success drivers of a future circular economy for plastics to contribute to the UN Sustainable Development Goals. Facing global challenges, the EU is fully committed to driving forward the implementation of the UN Sustainable Development Goals. Several of the goals and associated targets are of particular relevance to the Plastic Strategy, including Goals 8, 12 and 14. A better understanding of how the transition towards a circular economy for plastics would contribute to achieving the UN SDGs would align objectives and reinforce the impact of efforts.



PART III:

CIRCULAR AFTER-USE PATHWAYS FOR PLASTICS

While waste elimination through selection of materials, product design and business models should be prioritised, the tasks accomplished by plastics will lead to discarded materials at some point.

In a circular economy for plastics, all those materials need to be recycled in an effective system. The final part of this report reviews existing and emerging methods that can be used to create such a viable after-use economy for plastics.

6 COLLECTION AND SORTING

In 2016 plastics demand in Europe was 50 million tonnes, of which roughly 40 % were used in packaging (PlasticsEurope, 2018). This total demand is made up of 80 % thermoplastics such as PP, PE and PET, 15 % thermosets that cannot be remoulded or reheated, such as polyurethane (PU), epoxy resins, and phenolics, and 5 % of other, specialised materials. There is a well-established impression that the after-use collection, sorting and recycling systems of most, if not all, of these materials are underperforming. Often this is attributed to the increased material diversity and complexity, especially in comparison to other more homogeneous materials such as metals or glass (Esbensen & Velis, 2016 and Deloitte Sustainability, 2017). The rate of collection for recycling varies considerably across Europe, even within the same polymer type. For example, this rate ranges from 0 % for PET household films to 80 % for PET household bottles. As collection and sorting are crucial for after-use reprocessing, this chapter aims to provide further insights into this situation.

6.1 Collection and sorting across different regions

State of play

The capacity for collection, sorting and recycling differs across Europe and is insufficient to transition towards a circular economy for plastics. While collection and sorting are essential requirements to retain the value of products and materials, the existing infrastructure is insufficient in several places, or it needs to be modernised to enable high-quality recycling (European Commission, 2018j). As reflected in recent policymaking, separate collection of different material streams and investment in further sorting and recycling capacity are considered important, while avoiding infrastructural overcapacity for processing mixed waste, e.g. incineration (European Commission, 2018h and European Commission, 2018j).

Collection and sorting performance depends on a complex and continuously evolving plastics landscape. There are thousands of different plastics and additives, and there is increasing consensus that this complexity, especially in packaging, hinders effective source separation. Citizens seem to be puzzled about the many materials and formats, such as plastics films which are often not collected for recycling. In addition, the materials landscape is evolving constantly due to both established and emerging socioeconomic and material-level innovation trends, including (see also Section 5.4):

- **Lightweighting**. Examples include the replacement of metals (e.g. steel and or aluminium) with composites that are lighter, cheaper and can be formed into more complex shapes, and the replacement of glass beer bottles with plastic ones due to convenience and shatter-resistance (Farmer, 2013). Another example is the use of thinner PET water bottles, reducing resource use and greenhouse gas emissions, but also making recycling less attractive.

- **New materials and manufacturing techniques**. Lighter or new materials are often a result of new production technologies, including additive manufacturing, a combination of advanced composite materials with computational-aided engineering for structural property optimisation, and other novel approaches (Zhu, Li & Childs, 2018). There are continuous efforts in the direction of new materials. For example, in the case of polyolefins where HDPE provides new possibilities for lightweighting of blow-moulded rigid packaging (Sherman, 2014). Innovation trends affecting packaging include nanotechnology, active and intelligent packaging (e.g. indicating food freshness) and bio-based and/or biodegradable plastics. Other factors are decentralisation, localisation and down-scaling of manufacturing trends such as 3D-printing, and the emergence of wearables creating a new category of complex products, i.e. electrical and electronic equipment (EEE) incorporated into clothes (Farmer, 2013).

- **New business models and societal trends**. Changing food production, evolving cooking and eating lifestyles, international shipments and e-commerce, augmented reality and quick response codes; all these things introduce new needs for packaging. In addition, the aging European population, migration, urbanisation and adoption of global consumer values about what constitutes prosperity and well-being, all impact the type of plastics produced, used and disposed of.

- **Global trade**. Increased manufacturing outside Europe and imports, and international fast-moving consumer goods (FMCG) introduce increased challenges and questions on how to control waste material flows (Farmer, 2013).

These developments may affect plastic waste composition in a combination of ways. In the case of packaging, i.e. the largest plastics application in Europe and globally, the consumer goods and retail sectors play a critical role in the selection of materials. These sectors use packaging beyond preservation of content, and extend its function to communication and advertisement.

Both manual pre-sorting at home and centralised sorting bring their particular benefits and disadvantages regarding material stream quality and operational costs. It is unclear and debatable whether commingled collection critically impedes the quality of recycled plastics, or just increases the cost for some of the sorting, cleaning and final reprocessing. While it is established that materials pre-sorted at source enable better quality recyclate in general, some argue that mechanical biological treatment (MBT) plants, receiving mixed residual municipal solid waste, can also generate a pre-concentrate of mixed plastics of sufficient quality for recycling (Deloitte Sustainability, 2017). At the same time, these MBT plants would deliver equivalent yield and better cost-effectiveness (Feil, Pretz, Jansen & van Velzen, 2017). With this mind, some consider commingled collection as a compromise between losing recyclables due to high degrees of contamination when collected in mixed household waste, and soaring collection costs for too many single fractions, which can overcome the limitations of low material concentration in an area (Clausen, Althaus & Pretz, 2018).

There is, however, clear evidence that in settings lacking specific (financial) incentives for citizens, such as deposit-refund schemes, most material is captured by variations of commingled collection (Palmer, Ghita, Savage & Evans, 2009). In addition, detailed studies on Dutch PET recycling have found major differences in the composition of PET bottle products sourced from different collection systems (van Velzen, Brouwer & Molenveld, 2016). The deposit-refund schemes achieved higher-quality recyclate in comparison to separate collection and mechanical recovery schemes. Indeed, Dutch PET bottle products that originated from separate collection and mechanical recovery contained more contaminants and non-food PET flasks, barrier bottles, opaque PET bottles and non-bottle PET. In general, PET bottle products from Dutch deposit-refund systems contained few contaminants. This is attributed to the fact that the design of nearly all the bottles complied with the European PET Bottle Platform design guidelines and the products were subject to few sorting faults.

The bring-bank system is a collection method in which the waste is placed in larger collective containers spread across residential areas. Regarding its performance in separate collection yields, a model for a low-performing Portuguese region was able to explain 73 % of the variation. The variability was due to the number of inhabitants per bring-bank, the relative accessibility of bring banks, the degree of urbanisation, the number of school years attended, and the area itself (Oliveira, Sousa, Vaz & Dias-Ferreira, 2018). Another overview study argues that ‘economic incentives for waste segregation are very important and should be tested in pilot studies or through simulation games, because major differences between opportunity costs and costs for alternative treatment options may lead to unwanted behaviour by waste producers and/or citizens' (Friege, 2018). Furthermore, citizens' behaviour regarding the separation of valuables, their cultural background with respect to waste management, and social norms must be taken into account when planning collection schemes. Obviously, convenient access to collection systems is essential. In addition, citizens must become accustomed to these systems with long-term awareness-raising helping to optimise the successful collection of recyclables.

There are also views that the only major separation in municipal solid waste should be between organics and the rest, resulting in a two-bin system: a dry and a wet bin (Oosting, 2018). This system was tested between 2007 and 2010 in the urban area of Kassel, Germany (Ehrhard, 2009 and Cimpan, Maul, Jansen, Pretz & Wenzel, 2015). The aim was to increase capturing dry recyclables via centralised sorting systems. Overall, households placed 62 % of waste in the wet bin and 3 8% in the dry bin, and the materials recovered ranged from 53 to 56 % of the household waste generated. The pilot programme resulted in citizen satisfaction, CO_2e emission savings and high recycling rates, but also incurred 20-30 % higher overall costs compared to the system now in place.

While it allows adaptation to local conditions, the fragmentation of collection and sorting systems negatively affects their efficiency and cost-effectiveness. The variety of collection modes does not help the citizens manually pre-sorting at home to perform effectively, i.e. source separation (Hahladakis, Purnell, Iacovidou, Velis & Atseyinku, 2018). There is even wide variability of collection and pre-sorting rules within single entities such as organisations, local authorities, collection companies and regions. For example, England alone has 320 local authorities, deploying a wide variety of protocols for the collection of used plastics present in municipal solid waste (Hahladakis, Purnell, Iacovidou, Velis & Atseyinku, 2018). While different capture systems allow adaptation to geographic and socioeconomic conditions, there is an established impression that the fragmentation of systems currently in operation results in confusion. Therefore, it impedes the collection of after-use materials or it results in considerable contamination. For example, having realised this, some devolved administrations in the UK, for example Scotland, are currently orientated towards simplifying and standardising the collection schemes as part of a new charter (Charter for Household Recycling in Scotland, 2015). When adhering to the associated code of practice, local authorities commit to designing and establishing common collection schemes, and to introducing a deposit-refund scheme. In Italy, multiple studies have been conducted about incentivising separate collection, but there is still no in-depth understanding of which combinations of technical and social aspects work and why (Agovino, Casaccia, Crociata & Sacco, 2018 and De Feo & Polito, 2015). While harmonising systems would bring benefits, solutions need to be adapted to geographic and socio-economic conditions. For example, in Greece there is a substantial informal recycling sector, especially after the post-2008 financial crisis and large-scale immigration. Workers in the informal sector access the formal commingled recyclables collection bins and (illegally) remove recyclable items to recycle them informally. In combination with the already initially high rate of unintentional contamination through item misplacement, this results in bin content with high levels of contamination, severely impeding the financial viability of the scheme.

Lessons from the informal sector could improve the accuracy and effectiveness of manual pre-sorting at home. There may be opportunities for learning how to improve the manual pre-sorting at home performed by citizens by better understanding the skillset used by informal waste pickers in developing economies. For example, in Brazil, informal recyclers organised in a cooperative sort up to 17 grades of plastic, including 5 grades of PET. They achieve such detailed manual separation by using different senses, such as visual inspection and feeling the texture, and rapid tests, such as bending the item (Purshouse et al., 2017). Through such knowledge exchange, sorting plastics at home into much more detailed categories would deliver better quality recycled materials (Purshouse et al., 2017). This could be considered an example of so-called ‘social innovation’, which would contribute to the goal of advancing collaborative R&I between Africa and Europe in the area of waste management (European Commission, 2014a). Such improvements could also benefit manual sorting in centralised sorting centres, even though this activity is becoming rather rare in Europe, due to health and safety regulations and high labour costs.

Challenges and knowledge gaps

Due to the high and still increasing complexity of packaging and other plastic products, it is difficult to sort the different materials in a cost-effective way. The complexity gives rise to issues even within the same sector of activity and for similar applications, as the exact formulation of the plastic material might vary (Deloitte Sustainability, 2017). Even relatively widely collected items bring challenges. For example, clear PET bottles end up in the same material stream as clear PET trays, where the latter are more diverse through differences due to additives and the formation process. As a result, during the grinding steps of the recycling processes, bottles will be shredded into homogenous scraps while trays will tend to produce smaller scraps, more heterogeneous parts, and more dust which might not be efficiently recycled (FP7 GREEN PACK).

Product design is not or insufficiently adapted to sorting. Many of the obstacles in plastics collection systems are caused by choices in earlier stages of the value chain, such as the product design phase (H2020 New_InnoNet). Plastic products are often not designed for optimal collection and sorting. For example, the use of optical brighteners and UV stabilisers negatively impacts optical sorting beams. The prevalence of multi-material packaging and the related challenges have been discussed in Section 5.2 (see also industry initiatives, such as (CEFLEX)). Other issues relate to the use of small format packaging (e.g. lids and tear-offs) for which sorting is difficult, infrequently used resins for specific applications (e.g. PVC for food packaging), and highly nutrient-contaminated packaging (e.g. fast-food packaging) (World Economic Forum and Ellen MacArthur Foundation, 2017). A general trend towards lightweight materials and items, resulting in a lower weight to volume ratio, and increasing transport costs per tonne are squeezing margins for collectors and sorters.

Contamination of collected plastics further hinders sorting and recycling. Such contamination includes the presence of chemicals or materials not in scope of being sorted out, regardless of whether they are recyclable or not. Examples of contamination in small EEE appliances and consumer electronics include metallic inserts, foam, rubbers, labels, coatings, paints and lacquers that require too much effort to separate out (H2020 CloseWEEE).

Collection, sorting and recycling schemes and infrastructure are fragmented, insufficiently developed or absent. Collection and sorting systems have difficulties in keeping up with the rapid emergence of new materials across different sectors and regions. For example, until recently separate collection for trays was not available due to relatively low quantities. Hence, a cost-effective collection system was feasible only in limited, special cases based on separate contracts such as for catering and food delivery systems. The fragmentation and frequent modifications of collection schemes is another hurdle, as is the case for plastics with insufficient quantities (collected or potentially available) to support financially sustainable recycling, such as WEEE (H2020 CloseWEEE) (Palmer, Ghita, Savage & Evans, 2009). Insufficient collection infrastructure can, for example, be found for composites and emerging plastics (e.g. PLA or PEF in PET streams). The latter example also prompts the more general question of how to enable the introduction of new polymers from a collection point of view. In addition, there is insufficient sorting and reprocessing capacity in Europe. In fact, a 2012 study concluded a ‘lack of recycling and sorting capacity required to process the amounts of waste generated in the EU’ at that time (Deloitte Sustainability, 2017). Nowadays, the increased targets for recycling and the side effects of China’s much stricter importing rules are expected to result in additional amounts of used plastics having to be handled by a system that is already lacking capacity.

There is a lack of knowledge about variations in the collection system. There is a wealth of information on kerbside collection systems, but there is much less understanding of the alternatives, including drop-off systems, buy-back systems and deposit-refund schemes (Mwanza, Mbohwa & Telukdarie, 2018). While collection rates are tracked in some areas, the Wasteaware benchmark system of indicators recognises that the rate alone does not convey the full picture, since the quality of collected materials also has to be assessed (Wilson et al., 2015). Knowledge of the requirements for achieving effective collection and sorting of plastics is also insufficient. Even when certain players are aware of these needs, communication between the actors in the value chain who design materials, and those who collect, sort and recycle, is absent or limited, leading to information asymmetry. The negative perception about the potential public health implications of using higher levels of recycled plastics in products can further create barriers to incentivise collection.

Legislation on collection is implemented to different degrees across regions. The degree of implementation of legislation on separate collection is affected by the local authority and regional institutional quality (Wilson et al., 2015). For example, it has been argued that it is mainly due to institutional constraints that certain provinces in Italy did not achieve the targets set by law (Agovino, Garofalo & Mariani, 2018). Islands, due to isolation, seasonality (if touristic) and insufficient quantities to be collected, often face increased challenges in implementing the collection legislation.

There are major methodological questions about how much material is available to collect. It is not straightforward to assess how much of the plastics put on the market become collectable, which makes it challenging to size collection systems. In a Dutch case study, the total amount of plastic packaging waste generated by households and companies on an annual basis was calculated. The calculation resulted in 37 % lower amounts for the after-use baseline compared to market-entry-based data (FP7 W2Plastics). For specialist waste streams such as plastic-reinforced composite construction materials, there is no systematic recording and a separate collection is not established (H2020 FiberEUSe). Glass-fibre-reinforced plastic (GFRP) and carbon-fibre-reinforced plastic (CFRP) are usually not sorted out from mixed waste streams. Regarding assessment of after-use composite waste streams, data about occurrence, volumes and geographical distribution are rare. Therefore, estimates can only be based on assumptions about average lifetimes and past production volumes, whereas the actual volume of material stored within society can vary (e.g. products being kept in households beyond the expected lifetime). Current recycling innovation efforts are attempting to build new databases for the material collected, via obtaining *in situ* data, but using automated cloud-based data management solutions has proved costly. Hence, relevant innovation has been abandoned for more attainable but less automated solutions (H2020 ARENA).

Forecasting future volumes and emergence of new materials is difficult. New materials and volume distributions change constantly with technology developments and societal trends. Currently, little effort is being made to try to forecast these changes. Estimates are mainly attempted for new high-value sectors such as photovoltaics or EEE, but the overall level of understanding of the impact of social change, material innovation and the new digital industry is low. Quantified forecasting of waste for emerging after-use materials and products is also challenging because of methodological difficulties, as in the case of new photovoltaic panels (Peeters, Altamirano, Dewulf & Duflou, 2017).

Policy recommendations and R&I priorities

Policy recommendations

Ensure full implementation and enforcement of the EU waste legislation. This should guarantee proper collection and sorting of used materials across the EU. Member States should be encouraged to develop laws against improper disposal by industry and citizens alike, and to develop corresponding penalties.

Develop a mechanism for gathering and sharing information on collection and sorting performance. Guided by best practice, such a system should lead to simplification, standardisation and reduction of variability at all levels: design, manufacturing, retail, use, pre-sorting, collection, sorting and (organic) recycling (Dri, Canfora, Antonopoulos & Gaudillat, 2018; Esbensen & Velis, 2016 and Velis, Lerpiniere & Coronado, 2015). The incentives for simplification should be aligned across stages and sectors. Solutions for homogeneous streams are easier to define but the economies of scale are more difficult to achieve, and therefore need to be carefully assessed to check if they are worthwhile. Given the considerable challenges in designing for collection, sorting and recycling, the insights generated should be shared with collection and sorting sectors, hitherto often ignored in the initial materials and product innovation. Otherwise, these actors will continue to face challenges in coming up with solutions for resource recovery and value retention of highly heterogeneous and contaminated mixes (Esbensen & Velis, 2016).

Harmonise collection systems across the EU, allowing a certain degree of local adaptation to socioeconomic conditions. Given the high degree of collection system fragmentation, harmonisation of collection schemes can contribute to simplifying citizen participation and enable economies of scale (Hahladakis, Purnell, Iacovidou, Velis & Atseyinku, 2018). For example, Scotland has released a charter calling on local authorities to develop such harmonised collection solutions (Charter for Household Recycling in Scotland, 2015). This harmonisation will allow packaging producers and brand owners to design items fit for collection and sorting across Europe. A suitable regulatory framework could encourage and facilitate convergence of best practices, allowing for a reasonable level of local differentiation. The Commission will issue guidance on separate collection of several waste streams, including plastics (European Commission, 2018j).

R&I priorities

Provide funding for research on value capture optimisation of separate collection of plastics and/or other materials. Developing separate processes for specific waste streams has been flagged as an urgent need. However, the level of granularity of 'waste stream' is not easy to define. Therefore it is critical to better understand the compatible streams that can be co-collected and co-processed (H2020 New_InnoNet). In buildings, for example, the demolition process affects the quality of the products obtained. If selective demolition is applied, items with high recycling and reuse potential can be obtained, e.g. structural elements, equipment and furniture. Hence, demolition should be treated as management of the end-of-use phase of a building (FP7 ICOW).

Provide financial incentives for innovation in methodologies to accurately quantify and forecast the generation rate and source of emerging waste composition. The emerging digital technologies and societal trends offer a major opportunity to incorporate into the wave of innovation the requirements for embedding and costing in solutions for collection and sorting. In addition, this would provide ways to address the increased variability and contamination, which are key aspects of value drop at the end of the first-use cycle (Esbensen & Velis, 2016).

Provide funding for research into interdisciplinary solutions to manage and reduce plastics complexity at the application level, if beneficial from the economic, environmental and social perspective. A business-as-usual scenario would most likely just result in more complex and cross-contaminated material flows, increasing the current challenges (Velis, Lerpiniere & Coronado, 2015). To ensure emerging or changing sectors embed circularity in their activities and simplify the landscape right from the start, disruption of the current materials, products and business model innovation model is needed. Such disruption can be encouraged by incorporating socioeconomic and behavioural aspects into interdisciplinary efforts. The challenges of such research include establishing common terminology and applying compatible methodologies across disciplines. Lessons from collection and sorting systems prevalent in developing economies, such as detailed manual sorting of plastics performed by waste pickers, would provide insights for both manual pre-sorting and robotic sorting (Purshouse et al., 2017).

6.2 Improving collection and sorting through innovation

State of Play

Extended producer responsibility schemes for plastic products are in place across Europe, but implementation and scope differ widely. EPR schemes extend the producer responsibility to the after-use stage of a product's life cycle (see also Section 5.2). Such schemes exist, for example, for vehicles, electronic equipment and packaging. However, multiple non-standardised implementation schemes apply, with substantial differences between countries and sectors. There is experience with additional and/or narrower waste streams in certain countries. For example, only eight countries cover agricultural plastic films, Belgium covers disposable kitchenware and France covers textiles and furniture (Deloitte, 2014). Producer responsibility of the industries required to take part in EPR schemes is typically implemented as collective, rather than individual, via the setting up of collective producer responsibility organisation (PRO) schemes (Deloitte, 2014). The fees contributed by the PROs tend to cover all or a substantial part of the waste collection and reprocessing system as a net separate collection and treatment cost. Over time, their scope has extended well beyond financial and cash flow management into operational interventions, including data management, organising operations, launching bids and communication campaigns.

Performance and costs of the different EPR schemes vary a lot across regions. For example, for the packaging sector, recycling rates, which are often defined as the ratio of the quantity collected to that put on the market, ranged from 29 % (Malta) to 84 % (Denmark). Average fees charged to producers per tonne of packaging (household only) vary from less than EUR 20 (United Kingdom) to nearly EUR 200 (Austria) (Deloitte, 2014). The comparative cost-effectiveness of different EPRs is difficult to assess. For example, in 2010-2011 Belgium achieved high recycling rates above 80 % with comparatively modest PRO fees for both household and commercial & industrial (C&I) waste, while collecting only 65 (household) and 75 (C&I) kg/capita/year. The UK collected 176 kg/capita/year, with a recycling rate of 61 % due to much higher waste arising per capita in the UK, but less spending (EUR 11/capita) (Deloitte, 2014). Generic conclusions indicate that the best performing schemes are not, in most cases, the most expensive. However, the cheapest ones also fail to bring good recycling results. Fees paid by the producers vary greatly for all product categories, reflecting either a difference in scope and cost coverage, or in the actual net costs for the collection and treatment of waste (or both). No single EPR model emerges as the best performing and the most cost-effective (Deloitte, 2014).

Processing technology for after-use product handling is mainly focused on existing fossil-fuel-based plastic products. The driver of this focus seems to be dealing with the existing after-use products. Among the many projects, a few are FP7 POLYMARK, which aims to facilitate plastic waste identification for easier sorting, FP7 SUPERCLEANQ, which is developing quality control procedures for plastic waste, and FP7 ULTRAVISC, which is developing an ultrasonic detection technology.

New methods can increase the performance of separation, enabling sorting of materials currently out of scope in most markets. Novel systems can reach the (current) benchmark for separation accuracy up to 5-6 kg/m^3 (FP7 W2Plastics). However, if the feed rate exceeds what a particular device is designed for, quality drops sharply and this affects the quality of the subsequently recycled material. Cross-contamination can therefore be significant, e.g. 4-5 % HDPE in PP and 8-10 % PP in HDPE (FP7 W2Plastics). Improving the spectroscopic methods (e.g. through infrared, Raman or UV-VIS spectroscopy) can increase accuracy and help increase the types of polymers in scope for automated sorting.

One project assessed the ability to detect black items, as well as less common polymers such as PS, ABS and PLA. It was able to detect PLA and other biodegradable plastics when present in small amounts in a PET stream (0.01 %) and a HDPE stream (0.1 %). While several items are not yet detected by today's technologies, they could be in future with the right equipment, such as near-infrared spectroscopy (FP7 SUPERCLEANQ). As PLA has started to enter the market, it acts as a disrupting contaminant to larger volume streams and innovation to detect and separate it becomes crucial. Tracer- or marker-based sorting (see Section 5.3) could additionally increase sorting performance, recognising not just types of polymers but also different classes of compounds and items. If such technology was implemented in a standardised way, it could in principle help recyclers 'tune' the granularity of their recyclates according to demand and other market forces. Another project developed a dry-cleaning technology to make agricultural mulch film commercially viable for recycling by removing soil residue before transportation (FP7 START). Most of the mulch film market, expected to be worth over USD 4 billion by 2020 consists of LDPE (MarketsAndMarkets, 2016). If this film is not recycled it generates fragments that accumulate in the soil at an average rate of 460 kg/hectare per decade (OWS, 2017).

New (digital) technologies could further improve collection and sorting, for both source separation and centralised systems. Recent advances in robotics and sorting supported by AI are making automated item-picking technology commercially available (e.g. ZenRobotics, Max-AI). The key innovation of ZenRobotics is a machine-learning-based system, which gathers gigabytes of data on its environment, makes decisions and moves a robot arm in an unpredictable environment (H2020 ROBOLUTION). Its robotic sorter has been tested for its ability to pick plastics tubes. Max-AI robotic sorters are enabled by the AI-infused visual recognition capabilities of Sadako Technologies, which has been developing a real-time waste stream monitoring system (H2020 RUBSEE). Specialised AI-focused sorting companies and collaboration projects have been set up, such as INNOSORT, a consortium led by the Technological Institute of Denmark. Experiments are also being conducted on automatic waste collection. For example Volvo is working on autonomous vehicles that drive with small independent robots which can then leave the vehicle to pick up bins and bring them to the collection vehicle. Automated vacuum or pneumatic collection systems are available on the market and have been implemented in a few cases, including in Bergen, Norway, and in Helsinki, Finland (at Jätkäsaari, a new residential neighbourhood). Barking Riverside in East London, UK, provides another example using the Swedish Envac system for 11 000 homes/offices. A draft voluntary specification for relevant systems has been released in the UK (Draft PAS 908:2018). In this agreement, rigid plastics are considered as acceptable for handling, but the suitability of film or polystyrene depends on quantities, the system design and processing specifications. As indicated by the last example, these technologies mostly only cover collection or sorting with a narrow scope and there are throughput limitations. Nevertheless, current developments in AI indicate further opportunities to better sort used items, possibly in combination with optical or other technologies.

New technologies also offer another way to improve source separation. Small devices such as smartphones can use sensors to identify different materials and can be combined with new digital industry innovations (e.g. 'clever bins') to transform the effectiveness of pre-sorting at home. For more homogeneous specialist streams such agricultural films, efforts are being made to introduce IT collection and logistics support, such as the development of web-based logistical software to provide a means of managing all aspects of the collection and recycling process (FP7 START). Similarly, integrated systems are being developed for the specialist plastic stream of synthetic turf, including on-site vehicle-based removal and recycling (H2020 ARENA). There is already extensive scientific output on the mathematical optimisation of collection routes. In fact, multiple local authorities have optimised collection systems by implementing geographic information systems. Drone inspection is used in landfill monitoring, but its use in collection is limited. However, new services are beginning to appear on the market, such as applications for waste transportation and litter monitoring (Greaves, 2017). Specialised companies are emerging, but their scope and capability to scale up is still unclear.

Collection bins are now increasingly equipped with sensor-based systems that can communicate in real time. This technology opens up new possibilities ranging from optimising collection routes to tracking how full bins are (Ramos, de Morais & Barbosa-Póvoa, 2018). Such improvements offer costs savings in theory, but these still need to be demonstrated in practice. At home, gamification could offer opportunities to improve pre-sorting.

Challenges and Knowledge Gaps

There is a lack of information on the technical and economic performance of different EPR schemes. A detailed comparative study of the EU EPR schemes concluded that there is a severe lack of comparable information available on their technical and economic performance. It is unclear how much of the after-use plastics in these sectors are captured by EPR-supported schemes (Deloitte, 2014).

The impact of current EPR schemes on the design of products is unclear. A major challenge is the lack of clear evidence of a positive impact of EPR schemes on the ecodesign of products, such as by developing relevant targets or indicators. It is argued that by averaging the costs and risks among producers, individual companies are not sufficiently incentivised towards ecodesign, which is a tangible established dimension of the circular economy concept. This would in particular apply to decontamination of material flows and to provisioning for disassembly and (mechanical/chemical/organic) recyclability. In addition, considerations about reuse, refurbishment and remanufacturing were often not taken into account. Some experts argue from a theoretical point of view that EPR schemes incorporating bonus and/or penalty approaches are better. Examples of such systems include Fost Plus (Belgium) and Valorplast (Luxembourg), which combine a set tariff for packaging with a bonus/penalty system. In France, Citeo applies penalties for packaging made up of materials that are difficult to separate or recycle, along with bonuses for producers who improve awareness and make it easier for the packaging to be sorted or recycled in the current system. In Italy, modulated fees are in place in the packaging compliance scheme CONAI, in which plastic packaging is split into bands based on how easy it is to recycle and on which material stream it ends up in (Global Product Stewardship Council, 2018). The revised Waste Framework Directive will make eco-modulation of fees mandatory in cases of collective EPR schemes based on a number of criteria, including recyclability of products.

There is limited transparency on the effectiveness of EPR systems' objectives, cash flows and governance. This lack of visibility erodes the confidence in the utility and effectiveness of EPR schemes, whether individual or collective. In some sectors, such as vehicles, there is no competition between PROs. In addition, it is unclear how plastics innovation in materials, additives, and sorting capabilities towards a circular system is taken into account in the development and implementation of EPR schemes, if at all. As indicated by the actions of key players and relevant associations, potential tensions can arise between different EPR schemes. For example, bulk collection supported by general EPR schemes on the one hand, create tensions with deposit-refund and take-back schemes on the other. The latter schemes focus on the most valuable or readily recyclable after-use plastics, such as bottles of food-contact grade. Some argue that take-back targets should be combined with taxes on producers for non-collected waste fractions for more effective producer responsibility systems (Dubois, 2016).

New technologies and trends, such as additive manufacturing, e-commerce and smart devices, are not or only in a limited way integrated with current EPR architecture (Gu, Guo, Hall & Gu, 2018). New technologies and trends will create additional challenges, which should be taken into account. In addition, the integration of new technologies would help overcome some of the current issues, including enhancing transparency on performance and improving operations.

Technologies to improve collection and sorting quality and volumes are not being fully explored. Despite significant recent advances, there is insufficient progress in digital collection and separation techniques towards implementing them in practice and at scale. Two examples are the ability to sort out black trays and to identify food-grade quality, which are technically possible but not yet done, with significant opportunities for high-quality recycling lost. Technological challenges include density overlap and/or immiscibility of different material groups. Sorting technologies, including robotics and AI, still encounter throughput limitations and accuracy issues. In addition, there is a high capital investment cost for advanced sensor-based sorting, combined with the need for maintaining some form of technological standardisation. There is uncertainty regarding all aspects of automation and the new digital industry when it comes to a circular economy in general and in plastics in particular. New infrastructure systems seem to be tested only in newly planned developments rather than in retrofitting schemes, and their affordability need to be understood better.

Policy recommendations and R&I priorities

Policy recommendations

Develop a stewardship framework by facilitating structured sector-wide debates on its definition, the objectives and governance. This could include the responsibilities and roles of each actor, clearly defined along the whole product life cycle (Deloitte, 2014). The development should optimise synergies between different product stewardship schemes for individual products, such as deposit-refund and other EPR schemes. As different stewardship schemes bring different benefits and characteristics, it makes sense to combine them. In order to avoid unintended consequences or skewed incentives, they should be harmonised and used to reinforce their objectives.

Set up a system to steer individual stakeholders in a collective responsibility regime towards product design that better suits after-use collection and sorting, such as EPR schemes with modulated fees harmonised across the EU. The connection between fees paid by a producer to a collective scheme for their specific product, which currently prevails, and the circular economy, e.g. by designing for reuse, is currently weak. Creating a positive feedback mechanism to incentivise product design to improve after-use handling would be a powerful tool, for example through EPR schemes with modulated fees. The minimum general requirements on EPR as defined in the revised Waste Framework Directive (Article 8a) are already moving in this direction (European Commission, 2018h).

Create collaboration mechanisms to support industrial symbiosis in order to retain value of after-use plastics. Collection of sufficient quantities of after-use plastics to benefit from economies of scale is likely to require coordination between different sectors, such as packaging and textiles. However, there are often major logistical and technical barriers to overcome, such as difference in what EPR schemes are implemented. Another barrier is the difference in technical performance (i.e. quality and grades) required by different sectors, which may result in material incompatibilities during mechanical recycling. Value could be (partly) retained through cross-sectoral material exchanges or through high-value cascading. This would require facilitating the interface between different sectors and fostering a new cross-sectoral symbiosis. For example, after-use packaging plastics with lower specifications can be processed via mechanical recycling into automotive or electronic equipment.

Facilitate collaboration to ensure a greater level of openness and transparency between market players in order to retain value of after-use plastics. Information transparency (see Section 5.3) enables stakeholders in the value chain to keep track of the material content to ensure that product use and its after-use processing supports industrial symbiosis (Velis C., 2018).

Develop or facilitate the development of a mechanism to integrate different EPR schemes with new digital technologies to improve (transparency on) performance and mutual reinforcement. For example, the implications of robotic disassembly or smart tagging of materials and products, 3D printing and wearables could transform the information asymmetry that currently impedes effective producer responsibility systems (Gu, Guo, Hall & Gu, 2018). The facilitation of plastic-flow monitoring in the economy and throughout globalised geography is another aspect of the integration with digital technologies, and there is a need to explore how to use such information to create better and differentiated incentives within an EPR scheme.

Facilitate and fund capital investments in innovative waste sorting and monitoring equipment. By providing soft loans or other financial or tax incentives to municipalities and operators, sorting infrastructure can be upgraded to improve sorting fidelity and depth. Funding, for example in innovation, could partly be collected through other measures such as EPR systems.

R&I priorities

Provide financial incentives for innovation in development and testing of (digital) technologies for collection and sorting. Topics to be further explored include:

- Tagging, identification, collection, sorting and decontamination of after-use plastics, including combined efforts on different innovation fronts and with sufficient adaptation to socioeconomic and geographic realities across Europe (see also Section 5.3).
- Integration of engineering technical solutions with the socioeconomic aspects at the individual, public and governance level (Wilson et al., 2015).
- Optimal level of tolerable contamination for each collection system and an assessment of it within a wider system context comprising a suite of collection tools.
- Mobile processing of used plastics for islands or low-quantity specialised streams.
- Potential tensions and synergies from human versus new digital robotic-automated industry systems to arrive at new optimal arrangements, for much higher levels of collection for recycling as well as effective value retention when closing the cycle.
- Possibilities for negating the pre-sorting by effective downstream mechanical, automated or complex chemical separation technologies, based on a holistic impact assessment that includes environmental and social aspects.
- IT solutions to engage citizens to eradicate litter, fly-tipping and waste crime.
- Radical redesign of home, commercial and institutional environment architecture and infrastructure provisions in relation to the creation of waste, because this is the key point of value loss of used resources (Iacovidou et al., 2017).
- Pneumatic or underground storage with robotic collection.

Provide funding for research to understand the implications of implementing different EPR schemes (including deposit-refund systems) and the related infrastructure needs. Such research would lead to a better understanding of the implications of a much wider application of deposit-refund or take-back systems versus a situation starting from mixed flows, such as in residual waste. The impact of increased automation should also be included, as should the technical viability and affordability of retrofitting new tools or infrastructure solutions in existing systems versus building new systems to fit them. Demonstration projects with tailored detailed monitoring are needed, especially for retrofitting, to understand suitability at different population densities and for brownfield/regenerated areas.

7 MECHANICAL RECYCLING

7.1 Input and performance of mechanical recycling

State of play

Mechanical recycling brings economic and environmental benefits. A central principle in the circular economy is to preserve value in material cycles by maintaining the materials' structural integrity. Consequently, the most value-preserving cycles (or 'loops') are repairing/maintenance as well as reuse, for which there is significant potential especially in durable plastic products. It has been estimated that reuse can be an attractive option for at least 20% of plastic packaging currently on the market (World Economic Forum and Ellen MacArthur Foundation, 2017). However, for a large share of plastic packaging, recycling is crucial to create circular material flows, and the principal 'innermost' of different recycling loops is mechanical recycling. Mechanical recycling is a robust and comparatively efficient way of reprocessing plastics into new resin that can be put back into the value chain. The carbon footprint, expressed as GWP, of recycled plastics can be up to 10 times smaller than the one of a virgin equivalent (PlasticsEurope, 2011 and ALPLA, 2018). A recent study by the Swedish Environmental Protection Agency found that recycled plastics save about 1-1.5 kg CO_2/kg resin compared to the virgin material (results vary with different polymer types) (Stenmarck Å. et al., 2018). Another estimate states that each kg of recycled plastics gives energy savings of 130 000 kJ (Rahimi & García, 2017). Moreover, plastics recycling can not only provide a substantial CO_2 abatement opportunity, but it also has the potential to be economically attractive compared to much else that needs to happen to set the EU on a low-carbon path (Material Economics, 2018).

Currently, most important outlets for recycled plastics are not saturated, with rather low levels of virgin material substitution. Regarding plastic packaging (40% of all plastics demand in the EU), the four most important polymer types collected for recycling are PET mix, HDPE, LDPE and PP, resulting in a PET plus polyolefin rate of collection for recycling of 44% (including household as well as commercial and industrial waste) in 2014 in Europe (Deloitte Sustainability, 2017). Of the total volume collected for recycling, only 13% reaches European converters and 30% is exported, with not much information on its final fate. Incidentally, rejects during various sorting stages amount to about 1.5 million tonnes, which is comparable to the order of magnitude of what reaches the converters in Europe according to modelling estimates, excluding contrary items and moisture (Deloitte Sustainability, 2017). This 13% (2.15 million tonnes) of available packaging plastics in Europe is directed into the sectors of: packaging (15%, PET), packaging (18%, LDPE and HDPE), construction (25%), automotive (6.5%), electrical and electronic equipment (3%), fibres (5.6%) and other sectors (27%). All these sectors currently have much a higher demand for plastic materials at the converter stage: indicatively, the most pronounced difference is for packaging with 3.5 million tonnes for PET and 13.9 million tonnes for LDPE (Deloitte Sustainability, 2017). At present the most prevalent end uses are in the following the sectors:

- **Packaging**: in bottle-to-bottle applications for clear and transparent PET, but also through the production of sheets used in thermoforming processes.

- **Construction**: mainly for pipe production, insulation and carpets.

- **Automotive**: mainly for bumpers and for hidden parts.

- **EEE**: used for dark-coloured products, and irons, printers, fans, etc.
- **Fibres**: this market is one of the major applications of recyclate, especially for non-woven interlining fabric (e.g. chemical suits, protection overalls, etc.) and automotive interiors.
- **Others**: this category concerns smaller markets, such as furniture and consumer goods (e.g. clothes, hangers and boxes) and strapping.

Per recycled polymer type:

- **rPET** is mainly used in packaging (313 kilotonnes), fibres (121 kilotonnes) and other industries (80 kilotonnes);
- **rHDPE** is used in construction (321 kilotonnes), packaging (143 kilotonnes) and other industries (107 kilotonnes);
- **rPP** is mainly used in the automotive industry (125 kilotonnes), packaging (69 kilotonnes), construction (63 kilotonnes), EEE (53 kilotonnes) and other industries (76 kilotonnes);
- **rLDPE** is mainly used in packaging (180 kilotonnes), construction (150 kilotonnes) and other industries and end markets (320 kilotonnes).

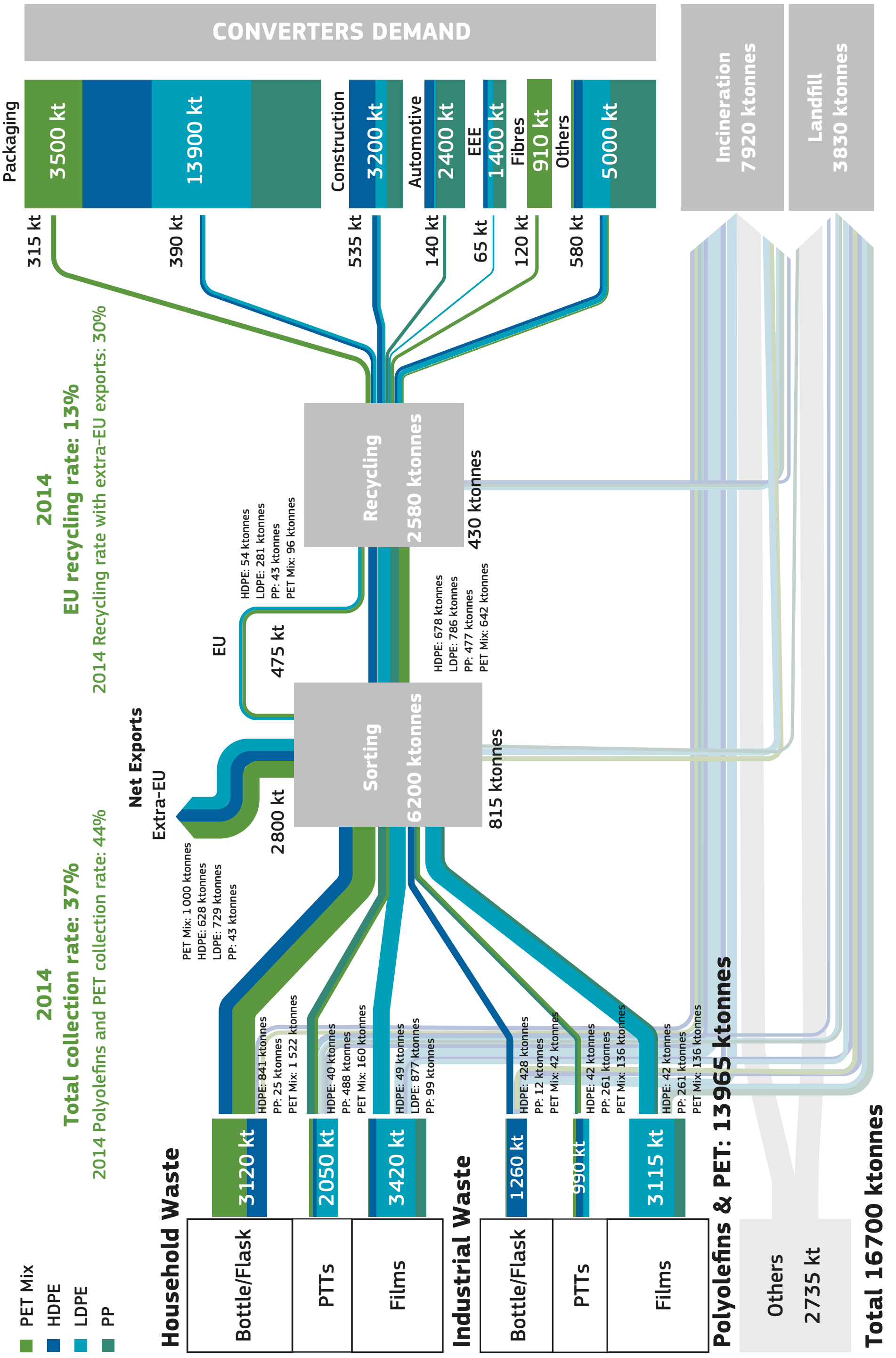
While PS and PVC were not in the scope of the study referred to, these polymers are recycled for certain applications (Deloitte Sustainability, 2017). For example, PVC recycling within the framework of VinylPlus, i.e. the voluntary sustainable development programme of the European PVC industry, reached 640 kilotonnes in 2017, with roughly half of the material coming from window frames and related products (VinylPlus). Extrapolation from five EU countries that generate 70 % of the EU's packaging plastic waste results in an overall use of 7 % of recyclate within the EU. The primary applications for using recycled content are construction (17 %), textile fibres (13 %), and packaging PET (9 %).

Plastics are often recycled into applications requiring lower material quality, partly due to a lack of a systemic perspective. To date, research has focused less on recycling solutions of complex packaging and the incorporation of recycled content into high-quality applications such as food contact packaging, and more on general collection and sorting practices combined with new technology innovation (H2020 New_InnoNet). Both areas are needed though to enable higher-quality recycling (see Section 5.3 for a discussion on technologies to create information transparency). In addition, little emphasis has been placed on the systemic aspects of mechanical recycling, including product design to facilitate the recycling step and the technologies needed to improve it. As a result, plastics often get recycled into applications with less strict quality requirements (e.g. non-food grade), which implies a loss of material value. Moreover, in many cases recycling is no longer an option, in which case the plastics is landfilled or incinerated and loses most, if not all, of the material value.

Mechanical recycling becomes increasingly difficult with higher material complexity. With the rapid increase in complex materials, in packaging and elsewhere, mechanical recycling can be expected to struggle due to two main reasons: firstly, the lack of adequate capacity to process complex materials into their purified components for subsequent use; secondly, issues with mixing when complex materials are not fully separated from mono-materials during collection and sorting. Below follows a brief summary of recent efforts to improve recycling of complex materials (e.g. composites, multilayer packaging, and associated adhesives).

- **Composites** are materials made by combining discrete different material components and are often manufactured with polymers, including both thermosets and thermoplastics. Examples include fibre-reinforced plastic (FRP), e.g. the combination of epoxy or vinyl esters and glass (i.e. GFRP), and carbon fibre and aramid, used in the automotive, construction and aerospace sectors (Shuaib & Mativenga, 2016). There is

Figure 23: Overview of European plastics streams, 2014


CONVERTERS DEMAND
Packaging
3500 kt
13900 kt
Construction
3200 kt
Automotive
2400 kt
EEE
1400 kt
Fibres
910 kt
Others
5000 kt
Incineration
7920 ktonnes
Landfill
3830 ktonnes
315 kt
390 kt
535 kt
140 kt
65 kt
120 kt
580 kt
2014
EU recycling rate: 13%
2014 Recycling rate with extra-EU exports: 30%
Recycling
2580 ktonnes
430 ktonnes
HDPE: 54 ktonnes
LDPE: 281 ktonnes
PP: 43 ktonnes
PET Mix: 96 ktonnes
EU
475 kt
HDPE: 678 ktonnes
LDPE: 786 ktonnes
PP: 477 ktonnes
PET Mix: 642 ktonnes
Net Exports
Extra-EU
2800 kt
Sorting
6200 ktonnes
815 ktonnes
PET Mix: 1 000 ktonnes
HDPE: 628 ktonnes
LDPE: 729 ktonnes
PP: 43 ktonnes
2014
Total collection rate: 37%
2014 Polyolefins and PET collection rate: 44%
HDPE: 841 ktonnes
PP: 25 ktonnes
PET Mix: 1 522 ktonnes
HDPE: 40 ktonnes
PP: 488 ktonnes
PET Mix: 160 ktonnes
HDPE: 49 ktonnes
LDPE: 877 ktonnes
PP: 99 ktonnes
HDPE: 428 ktonnes
PP: 12 ktonnes
PET Mix: 42 ktonnes
HDPE: 42 ktonnes
PP: 261 ktonnes
PET Mix: 136 ktonnes
HDPE: 42 ktonnes
PP: 261 ktonnes
PET Mix: 136 ktonnes
3120 kt
2050 kt
3420 kt
1260 kt
990 kt
3115 kt
Household Waste
Bottle/Flask
PTTs
Films
Industrial Waste
Bottle/Flask
PTTs
Films
Polyolefins & PET: 13965 ktonnes
Others
2735 kt
Total 16700 ktonnes
PET Mix
HDPE
LDPE
PP

Source: Deloitte Sustainability, 2017

an ongoing trend to make such materials using recycled content although recycling the composites remains notoriously difficult, especially when thermosets are used (FP7 W2PLASTICS). For GFRPs the most critical aspect to finding recycling methods that can separate the materials while retaining fibre length. There is evidence of potential energy savings when mechanically recycling GFRPs in comparison to virgin composites manufacturing, but the recycled polymers currently cannot match the technical specifications of the virgin ones (Shuaib & Mativenga, 2016). Innovation also exists in the sorting phase (i.e. mechanical separation), as in the case of a specialised zig-zag air classifier to refine the output grades (Palmer, Ghita, Savage & Evans, 2009). Typically, a sequence of dismantling, size reduction, and sorting is applied (H2020 FiberEUse).

- **Multilayer** materials refer to laminated films used in packaging, combining different polymer films to improve performance. Multiple material layers, such as the Tetra Pak board-film carton, could also be seen as belonging to this category. The materials may be glued or bonded together, resulting in complex products, e.g. food packaging containing five-layered materials made of polyamide and PET requiring two more binding layers to stick together (FP7 GREEN PACK). As discussed in other chapters, such material combinations are difficult or impossible to separate mechanically, and thus often require either chemical or biological treatment. One recently introduced method to address the inhomogeneous nature of multilayer materials is to add 'compatibilisers', i.e. chemicals that makes their components mix better into a composite resin (Hahladakis J. N., Velis, Weber, Iacovidou & Purnell, 2018). However, such a resin has relatively low fidelity and thus limited application areas. Partly due to this lower after-use value, the likelihood of it being collected for recycling remains an open question. In all cases, the alternative to mechanical recycling reverts to the need to collect and sort multilayer packaging (Section 6.1).

- **Adhesives** are polymers or other resins used to bind immiscible materials together, e.g. crystalline fibres with a polymer matrix, or separate polymer layers that do not stick together by themselves. Apart from being difficult to separate from the complex material, adhesives are typically present in comparatively small amounts, making them economically unattractive to recover. Furthermore, as many adhesives are thermosets, there is no viable method to recreate their original functionality once recovered. Clarity is needed on the intended after-use role of adhesives, during sorting, separating and disassembly, and on the possibility of simplifying or avoiding multi-polymer or multilayer materials that need adhesives in the first place.

Material cascades of composites could help retain some value. Since there is apparent interest in incorporating recycled materials into the polymer part of virgin FRPs, increased value retention could be achieved by using composites to cascade otherwise difficult-to-recycle materials. For example, using losses of manufacturing processes would lead to optimisation gains (Bains, 2013). However, the system behind such cascades needs to be better understood and engineered to ensure sufficient incentives to change the upstream design in place. Given the major industrial sectors and level of investments in the products involved (e.g. aerospace, construction and energy), the production, use and after-use processing of these materials should be increasingly considered explicitly and upfront. In general, more clarity is needed on how composites fit into a circular economy, and how value can be retained through collaboration of different actors within their existing or new capabilities, including the impact on their responsibilities (H2020 FiberEUse).

At present, cement kilns often offer the only viable option for handling used composites. In the absence of feasible recycling methods, co-processing of composites in cement kilns, both as a source of fuel and secondary materials, has become increasingly popular in Europe (H2020 FiberE-

Use). The inorganic components (e.g. glass) are incorporated into to the clinker output, while the organic part (e.g. polymers and additives) becomes an alternative fuel that displaces virgin fuels (e.g. coal, oil and gas). The otherwise common practice of incineration to recover energy is challenging with FRPs because of the clogging of bag-filter air pollution control equipment, hence the co-processing route in cement kilns (Limburg, Stockschläder & Quicker, 2017). Typically, contracts for the supply of alternative fuels and raw materials to cement kilns are short term (months to years) and are therefore less likely to generate market lock-in. In contrast, contracts for waste incineration tend to operate with guarantees of sufficient supply of the order of 25 years.

Challenges and knowledge gaps

Lack of quality, competitive pricing and regulations make it difficult for mechanically recycled plastics to compete with virgin plastics. The current mix and contamination level of collected and sorted after-use plastics going to mechanical recycling, in combination with the available processing technologies, mean that the compounds produced from recycled resin are mainly used for lower quality products (e.g. bin bags, recycled bins and plastic furniture). Yet they are sold at 70-80% of the price for virgin plastics (FP7 W2Plastics). Given the already low price of virgin material and the relatively low discount compared to quality drop for recycled plastics, it is perhaps not surprising that the economic arguments for incorporating recycled plastics are weak. In addition, users of recycled plastics may actually be subject to waste legislation, including the possible need for a waste treatment permit when handling or processing recycled plastics

With high uncertainty about input material composition and future demand, designing a mechanical recycling system fit for purpose is difficult. It is impossible to determine an effective mechanical recycling system without taking into account how the plastics system as a whole will function. Aspects affecting the recycling operations and business case cover the entire value chain, including business models (e.g. deposit-refund schemes for specific containers), product design (e.g. design for disassembly), societal and marketing trends (e.g. growth of multilayer packaging), material choices (e.g. recycling capacity for PLA or PEF), and the role of chemical recycling (e.g. mechanical recycling co-location with chemical recycling). While the shortcomings of the recycling system today are well-known, e.g. its inability to produce high-quality recycled materials, solutions to address them rely heavily on external factors upstream in the plastics value chain.

In cascading, composite quality loss and contamination is an issue. A carefully designed cascading system could help retain the material value of composite materials that are not (yet) designed for easy separation. However, it is difficult to envision how to achieve such a system as current technologies lead to significant quality loss of materials that are generally employed for high-performance tasks. For example, production-based blending leads to shortening of FRP fibres during every additional life cycle (Limburg, Stockschläder & Quicker, 2017). For CFRP, the overall environmental assessment of such separation technologies is generally positive, but matching is required with the intended new cycle application (Dieterle, Seiler & Viere, 2017). In construction, there is a lack of commercially viable market outlets for both CFRP and GFRP, and little consistency in the categorisation of composites (Bains, 2013). Because complex materials outside the packaging sector have longer use phases, there is also a risk of contamination from legacy substances continuing to appear for a long time. Finally, many composites are so complex that even cascading recycling is difficult. One illustrative example is screen and monitor housings that may be coated with a metallic lacquer on the inside (H2020 CloseWEEE). Due to the specialised capabilities required to reprocess some composites it has been suggested that large-scale waste managers may want to vertically integrate into both recycling and (re)manufacturing of such materials to bypass the value-chain fragmentation (H2020 FiberEUse).

Policy recommendations and R&I priorities

Policy recommendations

Set up regulatory requirements to stimulate demand for recycled content in general, and in high-quality applications in particular. Such market signals can be expected to drive investment and innovation towards improved recycling yields and quality. Measures could include supporting a well-functioning secondary materials market, and targets for recycled content and quality of recycled material. Measures should also take into account safety aspects (e.g. hazardous legacy elements) and implementation (e.g. method to verify recycled content), as for example exists for FCMs (European Commission, 2008a). Recognising that low-quality recycling is not enough to move towards a circular economy for plastics, as significant material value is lost, it is important to ensure high-quality recycled materials.

Set up fiscal framework to support the uptake of recycled polymers. One of the reasons virgin plastics comes at such a low price is the externalisation of many of their costs (see also Section 7.3 and 8.1). Rebalancing true cost of virgin plastics, including environmental and social impact, can improve competitiveness of recycled plastics (see e.g. CVORR). Measures could include VAT reduction for use of recycled plastics, or different EPR fees for virgin versus recycled content. These fiscal measures can be mutually reinforcing with regulatory ones, such as targets on minimum recycled content.

Set up a cross-value chain platform to discuss the role of mechanical recycling in a future circular plastics system. Such a platform should take into account emerging technologies, e.g. traceability systems (Section 5.3) and depolymerisation (Section 8.1). It should also identify key system design and investment needs at EU and national level.

Provide business guidance on value-preserving cascading or final-sink treatment of legacy composite materials. The guidelines should help decide how to design the most economically productive pathways and handle legacy substances.

R&I priorities

Provide financial incentives for innovation in more efficient and economic solutions for mechanical recycling of polymer materials. Improved recycling processes is one key component of achieving higher-quality recycled materials at competitive pricing. Incentives could include grants, equity funding and public procurement.

7.2 Innovation towards cost-effective high-quality mechanical recycling

State of play

Successful commercial application of recycled food-grade packaging typically uses plastics from beverage containers. PET beverage containers are among the most frequently collected plastics, and are relatively homogenous and feasible to clean (FP7 GREEN PACK). Strong demand compared to a still limited supply, driven by the brand value of using recycled plastics can to some extent explain the relatively high price point of recycled PET (FP7 SUPERCLEANQ). Combined with conserved mechanical properties through the recycling process, recycled bottle PET enjoys a fairly large range of potential food-grade applications. Commercial use in new bottles is already commonplace, such as in the Innocent juice brand bottles, or in separate bottle-to-bottle recycling streams. While there are limitations on how much recycled PET can be used in bottles of a given quality, evidence points to potential for improvement. If the quality of the recycled resin is improved, current recycled content limits of 20-30 % could be increased to 50 %, and for thermoformed products from around 50 % to 75-100 % (FP7 GREEN PACK). A recent innovation project demonstrated high performance and recyclability of 'Ecopet' trays made from recycled PET (FP7 ECOPET).

Mixing of multiple grades, loss of functionality and cross-contamination during use and collection phases result in below-virgin quality of mechanically recycled polymers. Due to the presence of other grades within any single recycled polymer type, mechanically recycled materials will be less pure than any single virgin grade. While sorting can become more granular due to new practices or technologies (e.g. tracers or markers), this cross-contamination will continue to result in mechanically recycled plastics below virgin quality in the foreseeable future. Moreover, the presence of additives, functionality loss over time and unintended contamination during use, collection and reprocessing (e.g. melting), all contribute to the further reduction of material specificity, and thus lower quality. Additives though could also be a way to improve the ability to process and the performance of recycled plastics. For example, some thermoplastics can be made more recyclable with the right filler content. Finding the right trade-off between material specificity and enhanced processing is thus key to optimising the value of recycled plastics, while keeping in mind the importance of being able to reprocess recycled content again (FP7 GREEN PACK). At the same time, there is compelling evidence that the uncertainty in the chemical composition level of recycled plastics hampers a clean-material-flow circular economy. There have been recent efforts to list and categorise relevant substances, but they are incomplete given the lack of transparency on the material composition of virgin plastics and in particular recyclates (Hahladakis J. N., Velis, Weber, Iacovidou & Purnell, 2018; Stenmarck Å. et al., 2017; Halden R. U., 2010; Hauser & Calafat, 2005 and Sjödin, Patterson Jr & Bergman Åke, 2003).

While polymers can undergo several loops of mechanical reprocessing, the mixing of grades and additives along with rapid loss of information often makes more than one loop unfeasible. Polymers lose some of their physical properties due to thermal decomposition during conversion unit operations (e.g. extrusion or moulding). However, this process is slow and one could envision an individual polymer undergoing multiple loops in the same application before it loses its main properties, at least if supported by a portion of virgin or chemically recycled resin. But due to the loss of integrity and quality from mixing and contamination, the vast majority of recycling is currently of the cascading type, i.e. the recycled polymer is used in an application that differs from the original one and has a different (typically lower) set of quality requirements. In general, the quality of the recycled resin is negatively impacted by almost all contaminants. For example, colour and transparency are sensitive to residual pigments. Particles, adhesives and other additives can lead to haze formation and discolouring. EVOH causes cross-linking with PET, risking gel formation, and PVC can lead to benzene vapour during reprocessing at higher temperature (van Velzen, Brouwer & Molenveld, 2016 and Velis, Lerpiniere & Coronado, 2015).

Overall, 'standard' recycling operations are able to generate recycled PET of sufficient quality from materials sourced from deposit-return systems, but of inferior quality from the source-separated and mechanically sorted collection streams. The use of advanced sorting is able to remove contaminants for the latter and produce high-quality rPET, but it results in considerable mass losses as rejects (low yield). The impact of using a more intense sorting standard (DKR 325, rather than 328-1) on the quality of recycled PET has been shown to be small, suggesting the contaminants originate from within the PET items (i.e. design-induced contamination) (van Velzen, Brouwer & Molenveld, Techical quality of rPET).

Multiple technologies exist to remove additives in both packaging and durable goods, but implementation is still limited. In durable goods (e.g. automotive and electronics), the plastics often have a higher inherent value, creating a stronger incentive to purify it. In WEEE plastics such as ABS and PS, significant effort has gone into removing brominated flame retardants and other additives that raise concerns (H2020 CloseWEEE). In packaging, some 'uncontrolled' removal of volatile contaminants occurs due to evaporation or transformation during extrusion, which leads to emissions and uncertainties about both the environmental and occupational health impact (FP7 BANUS). A co-extrusion process with a venting section, where a vacuum pumping system removes volatiles from ink degradation, and a filtering section to remove contaminant particles, is a possible technical solution under development. A number of decontamination technologies exist, from chemical stripping to remove coatings to alternative extrusion dealing with heavily printed films, albeit not implemented at scale (H2020 CLIPP PLUS). The Spanish start-up Cadel Deinking has a technology to remove print inks from plastic packaging to make the recycled resin more homogenous. So far, the main application has been to reprocess off-spec products, but de-inking technology could in principle be used to purify after-use plastics too. Decontamination options for embedded inks include mechanical ones such as particle blasting, compression vibration and cryogenic grinding; and chemical ones such as chemical stripping or hydrolysis via high temperature and alkaline treatment, liquid cyclone and melt filtration (H2020 CLIPP PLUS).

The basic ability to remove unwanted items can be provided by tracers or markers. Chemical tracers or (digital) makers in plastic products can be used to indicate their origin, intended use and intended after-use pathways (see Section 5.3). However, such markers or tracers do not capture information gained during the use phase and therefore cannot provide information about any contaminants added along the way. The simplest and most developed use case is the separation of food-grade and non-food-grade PET bottle recycling, with the PRISM project recently having finished a series of pilot trials (van Velzen, Brouwer & Molenveld, 2016). Evidence that the rare-earth-metal-based fluorescent tracers are removable during recycling needs to be established. If implemented, tracers or markers can in principle designate a plastic item for a specific after-use pathway to meet stricter standards, e.g. negative sorting of non-food-grade items. Contaminants that need advanced sorting techniques, such as sieving, flake sorting and colour sorting, to be removed include PVC, PS, POM, glass, silicone, and multilayer barriers films (van Velzen, Brouwer & Molenveld, 2016). Chemical tracers could offer a technical solution since they can be integrated into the resin and are not dependent on whether sorting happens before or after flaking. For pre-shredding detection, relatively simple technologies such as QR codes can be used to get information about a material's composition and origin and, to some extent, its history (H2020 ARENA).

Challenges and knowledge gaps

Despite relatively high-yield recycling for rigid mono-material packaging, challenges due to design or material factors remain (Velis, Lerpiniere & Coronado, 2015). First, contaminants from the use phase may enter the recycling stream, both from food and non-food packaging, even after sorting and washing. They include food residues, detergents, personal care products and chemical cleaners (Dvorak, Kosior & Moody, 2011). Commingling adds to the challenge of using recycled plastics in food-grade applications. While cleaning them out can be efficient, some substances present in personal care products, e.g. hexyl salicylate and isopropyl myristate, have high boiling points and low volatility, making them difficult to remove at the low temperature used to produce food-grade recycled plastics (Dvorak, Kosior & Moody, 2011). Certain measures, including the EFSA Criteria for PET recycling, require demonstration through a challenge test to ensure accidental contamination does not exceed a set limit (European Food Safety Authority, 2011). Second, inherent material degradation may require the replenishment of additives or complementary materials. For example, PP is photosensitive and requires new photo-stabilisers to restore functionality. It is difficult to know exactly how much recycled resins need to be 'upgraded' since transparency on the status of the input material is lacking.

High-quality demand even in applications where not technically necessary limits the applicability of mechanically recycled plastics. Virgin-grade plastics can be purchased with very specific performance and desired aesthetics, while recycled resins struggle to be as transparent, glossy or vividly coloured as their virgin competitors. This leads to the question of how to create acceptable standards for recycled materials, e.g. regarding aesthetics, rather than trying to push the upstream processing boundaries just for aesthetic rather than functional reasons (FP7 GREEN PACK and H2020 CloseWEEE).

Current mechanical recycling systems are not designed to effectively remove contaminants. For example, it has been suggested that only slightly higher levels of contamination of after-use PET (which would likely be the case if more PET was collected overall) would make recycling would too expensive at current market prices. Another dimension to consider is that the optimal technology for rigid and flexible packaging differ, indicating that if one requires high-quality recycling of both rigid and flexible packaging, two parallel operations would be needed (H2020 CLIPP PLUS). Investing in innovation and development of the capacity to handle contaminants therefore appears to be key.

Even with downgraded quality specifications for recycled plastics, the lack of information about content makes it difficult to build an effective after-use market. Arguably, the exchange of after-use materials between different applications (including different sectors) creates flexibility and resilience in such a market. However, if the used resin collected ends up being reprocessed to be recovered in a substantially different type of application, the property requirements may be very different. When there is insufficient information about the material composition and its compatibility with the new application, such uncertainty limits the potential applications even for a first additional cycle (and even more so for multiple cycles) (Hahladakis J. N., Velis, Weber, Iacovidou & Purnell, 2018 and Velis, Lerpiniere & Coronado, 2015). Given the current lack of transparency on what material compositions enter the market in the first place, the mechanical recycling sector is in a poor position to identify (or remove) substances that would contaminate a particular secondary application. It is important to describe how technical and engineering properties relate to the material value and the retention (or destruction or replenishment of such value) during the recycling process, as is advocated by novel sustainability assessment methodologies such as 'Complex Value Optimization for Resource Recovery' (CVORR) (Iacovidou et al., 2017; Millward-Hopkins et al., 2018 and Iacovidou et al., 2017).

New materials and other innovations continuously disrupt the recycling process. As stated previously, any new material or additive on the market increases the complexity of the after-use material flows and could potentially disrupt established processes. While no innovation would be possible without allowing some of this disruption, it is worth emphasising that lack of careful consideration of the full cycle of a material within the system can lead to unintended negative consequences that exceed the benefits brought by the new innovation. One often-mentioned example is PLA in the recycling stream; often intended to be composted, small amounts end up in the recycling stream. PLA degrades at the processing temperature of PET (> 260 °C), thus even < 0.1 % PLA contamination in recycled PET is unacceptable (FP7 SUPERCLEANQ). As shown above, improved spectroscopy enables identification of PLA in the PET stream, but removing it comes with an added cost.

The attention paid to the decontamination of brominated legacy compounds from WEEE, including recovering bromine, is limited. There are multiple challenges in dealing with legacy brominated substances in WEEE, but more efforts are needed because of health reasons (Lucas et al., 2018a and Lucas et al., 2018b). Some innovators argue that there exist viable technologies to retrieve bromine from natural resources, which could potentially be adapted to remove and recover brominated flame retardants in WEEE. However, these are currently not being considered, and the efforts to remove bromine from durable goods is generally quite low (H2020 CloseWEEE).

There is as yet no clear idea of how to handle chemical tracers that may enter the market. Tracers in their most advanced form are currently rare-earth-metal-based fluorescent molecules, with a high inherent value. Yet, as their intended use case is to be loaded just above some detection limit, the economic viability of recovering them from the recycled resin may be low. Questions therefore arise about whether they will be safe ‘contaminants’ in food-grade plastics, and if they can remain as background substances without disrupting subsequent chemical tracer identification.

Policy recommendations and R&I priorities

Policy recommendations

Set regulatory requirements for product design to drive innovation towards products that can be effectively recycled where they are put on the market. At the moment, recycling innovation constantly lags behind upstream innovation on polymers, additives and plastic materials, often negatively impacting the yield or quality of recycling. Hence, upstream measures should drive innovations that are harmonised with, and not disruptive to, the recycling system. Implementation of ecodesign guidelines can support cost-effective disassembly and recycling.

Set regulatory requirements to remove brominated flame retardants and recover bromine. As discussed in Chapter 2, recycling can lead to the presence of chemicals of concern in new products, of which brominated flame retardants form an important category.

Develop and provide business guidance on introducing new materials or substances to the market to prevent disruption of the recycling system. Such guidelines should be triggered whenever there is a risk of negative effects exceeding the long-term benefits, operating according to the precautionary principle.

Develop a strategy to deal with the potential future presence of chemical tracers or other markers in plastics. As explained in Section 5.3, some form of chemical tracers or other markers might be implemented to provide information transparency. In anticipation of the introduction of these substances, a strategy is needed to understand how they could affect recycling and how they can be dealt with.

Develop a framework to improve transparency on material composition of primary and secondary plastics. Such a framework would help to control unwanted substances present in or created by reprocessing, leading to higher value retention in circular material flows (Velis & Brunner, 2013). Creating a suitable list of such substances will require cross-sectoral collaboration, building trust between different stakeholders. The substances can be split into two categories: those that are preferably eliminated from the circular material cycle and those which are showstoppers for a high-value or fit-for-purpose use of the recycled resin, the latter inevitably being application-specific. Tracking would require procedures, standards (existing and new) and transparency (equitable access to information, combatting information disparity between players), without compromising the potential for innovation and commercialisation. Examples of efforts to generate (confidential) sharing and exchange of sensitive information between business players within an industrial symbiosis model exist already, such as H2020 SHAREBOX. Additionally, a transparency framework should enable a higher level of wider stakeholder scrutiny. Such efforts would deliver benefits for increased transparency, which is considered a critical enabling factor in moving towards a circular economy (H2020 New_InnoNet).

Develop a vision for a holistic recycling system in Europe, incorporating mechanical, chemical and organic recycling. Such a vision should identify the necessary technologies a best-practice recycling system needs in order to be able to remove necessary contaminants and deliver the recycled plastic quality the market demands. It also should help in understanding how different forms of recycling can work in mutually reinforcing way.

R&I priorities

Provide financial incentives for innovation in solutions that manage or reduce the plastics landscape complexity at application level. Such solutions span across the design, production, use, and after-use phases of plastic materials. For example, a simplification of the portfolio of virgin polymers, additives and filler materials for specific applications would positively affect the volume and quality (in terms of contamination) of materials collected for recycling within one stream. Incentives could include grants, equity funding and public procurement.

Provide financial incentives for innovation in recycling technologies that improve the quality of mechanically recycled polymers. The higher the quality of recycled materials, e.g. for use in applications with strict requirements, the greater the value retained, and the larger the potential market for recycled materials.

Provide funding to support large-scale piloting and scale-up of existing decontamination technologies. The huge material diversity of plastics and types of contamination necessitate a diversity of specialised decontamination techniques. Transfer of contaminants to other media (air and water) during decontamination is substantial and needs to be further scrutinised with a view to overall environmental performance and occupational health and safety.

Provide funding to understand the mechanisms, routes and systemic reasons for the successful use of recycled plastics in certain applications, and its replication potential. Alongside financial viability, it is key to understand the socioeconomic drivers for acceptance of recycled materials are. It is also important to establish to the difference between the actual and perceived technical material performance from multiple aspects.

7.3 Enabling an effective, well-functioning secondary materials market

State of play

Reliance on exports of after-use plastics has left the European market underdeveloped, while creating significant negative externalities abroad. In the last 15 years, Europe has developed a strong dependence on exports of after-use plastics to China – a situation that abruptly changed recently due to the 'National Sword' policy. This seemingly convenient route for collected plastics has meant that European markets have not been as strongly incentivised to innovate to improve and find applications for recycled plastics. While it is impossible to estimate the exact effect, it is reasonable to assume it has set quality levels and real recycling rates back several years (Velis, 2014). In addition, the export's implications outside Europe are significant. An unspecified fraction of the exports to the developing economies (mainly China) has been processed under sub-optimal conditions. Examples of such conditions include lack of wastewater management, open burning of rejects or contaminants, potential use of unsuitable additives, and low-quality counterfeit items production. Following a suspected 'least environmental protection' pathway, plastics flow across borders and materials of low financial value (or even negative value, as for toxic waste) tend to end up in areas where the fewest environmental protection standards are in place (Crang, Hughes & Gregson, 2013). In addition, legislation in these areas is often only partly enforced, in combination with low wages for manual processing, as in the case of ship-breaking or treating hazardous fractions of WEEE (Kirby & Lora Wainwright, 2014; Cao, 2019 and Velis C. A., 2015). There is insufficient quantified evidence on the impact of such practices, e.g. in the form of wider assessments taking into account the socio-economic implications (Iacovidou et al., 2017 and

Millward-Hopkins et al., 2018). However, it can be concluded that some of these recycling practices are against the genuine spirit of the waste hierarchy or the circular economy as guiding principles.

To recycle more plastics, Europe needs a bigger market for recycled plastics, highlighting the need for demand. If significantly higher recycling targets are to be achieved with reduced extra-EU exports and a more strictly defined 'recycling rate', considerable new market outlets for recycled plastics need be developed within Europe (Deloitte Sustainability, 2017). A plastic packaging recycling target of 55% by 2025 means absorbing 10 million tonnes, which is more than twice the current volume, and consequently means doubling the demand. A challenging aspect of this goal is that recycled plastics are more generic than the sometime highly specialised virgin materials; another is that prices are not competitive enough. One route to improving the competitiveness of recycled material is to diversify recycling processes, for example by offering on-site processing into new packaging to reduce transportation costs (H2020 ARENA).

Large margins for safety and specific quality requirements hinder the uptake of recycled materials. In general, business tends to use wide safety margins for requirements concerning consumer safety for several reasons, including compliance with regulatory requirements and mitigating brand risk. However, these measures could lead to unnecessary avoidance of recycled content. In the case of PET bottles, EFSA has set a 5% limit on non-food-grade material in food-grade material input for recycling, which some experts have suggested is overly cautious (van Velzen, Brouwer & Molenveld, 2016). In addition, the multiplicity of resins, combined with the complexity and overall variability in collection and sorting, results in great difficulties in demonstrating compliance for specific use requirements, such as odour and colour (Deloitte Sustainability, 2017). Similar considerations affect materials choice during the design phase, including for example the refusal of more greyish PET materials for water bottles, or concerns raised about mechanical properties or hazardous chemical migration.

The price difference between virgin and recycled plastics is a crucial challenge. In most cases, recycled materials are desirable only if they are traded at a significantly lower price than the equivalent virgin grades to make up for the loss of performance (and aesthetic appeal), which affects the viability of recycling businesses (Velis, Lerpiniere & Coronado, 2015). While it can be argued that virgin plastics are artificially cheap due to negative externalities not being priced in, related costs are difficult to internalise in a systematic and fair way. Hence it is hard to express a much more comprehensive understanding of what 'value' consists of, and how it can be reflected in pricing. Pricing in 'positive externalities' might be more feasible: some countries, such as China, have introduced VAT reductions to incentivise the uptake of recycled resources and plastics in particular, e.g. 10% discount on VAT for manufactures achieving 100% recycled plastics use (Meng & Yoshida, 2012).

Some standards for determining recycled content and traceability in plastics are in place in Europe. Being able to uniformly determine and report on recycled content in plastics is a cornerstone of a functioning after-use market, as it fosters transparency and comparability. There are some European standards in use, for example BS EN 15343:2007 specifies procedures for the traceability of recycled plastics, so providing the basis for calculating the recycled content of a product. A series of standards for the characterisation of recyclate exist (e.g. for PET, PS, PE and PVC). The rationale of the standards focuses on ensuring that technical functionality has been retained after use and that there is no cross-contamination (H2020 CLIPP PLUS). The voluntary certification scheme EuCertPlast, aims to recognise post-consumer plastics recycling by providing a quality label for the incorporation of recycled plastic in packaging. It specifies the procedures needed for the traceability and assessment of recycled content (H2020 New_InnoNet).

Quality standards and tolerance levels for contamination of recycled plastics differ across applications. The acceptable quality for sorted after-use plastics going into reprocessing depends on what the final output is going to be and the specific processing capabilities. For example, PP and HDPE mixed pre-concentrates are not acceptable to many facilities that lack their own flake-separation steps (FP7 W2Plastics). A number of relevant quality standards for recycled resin exist for different polymers, e.g. DKR-324 for PP and DKR 328-1 for PET. The European PET Bottle Platform set up its 'Quick Test QT500 Oven test for regrind PET flakes' in 2010 (EPBP, 2010). Within reprocessing plants, internal quality control standards are set, and in-house laboratories may be following procedures customised to their own inputs, production and outputs. Converters, however, develop their own understanding of quality requirements and tolerance for contamination. Since virgin, uncontaminated plastics are cheap and readily available, such tolerance levels generally become low, to the point where less than 95 % purity is too low to have any real chance of achieving a market at scale (H2020 CloseWEEE). Spectroscopy-based quality assurance tests are being developed (FP7 W2Plastics), which may help improve quality levels in the long term.

An EU-wide standard for different grade qualities for recycled plastics would be desirable but does not yet exist beyond development stage. Market-wide standardisation helps to scale the after-use market, as has been the case with classifying the grades of used paper/board (into 192 categories) with a European standard (Velis, Lerpiniere & Coronado, Circular Economy: Closing the Loops, 2015). However, an equivalent standard for plastics does not exist, and given the challenge of persistent legacy substances, it is arguably more difficult than with paper (REACH applies to the recovered materials to be used in new products). Projects to assist the development of parts of such a standard exist and have, for example, focused on a classification based on detection of selected compounds in food-grade PET (FP7 SUPERCLEANQ). However, they generally have a narrow scope and do not cover all stages of closing the cycle.

The EU could possibly source high-quality affordable recycled plastics from developing economies, while supporting low-income households. Supply of recycled plastics is global, not least for the currently most marketable grades, such as transparent PET and HDPE. The material entering the markets from developing economies is mostly collected and sorted manually by typically marginalised waste pickers from the informal recycling sector (IRS) (Velis C., 2017). Trading in a collaborative mode of operation would involve knowledge exchange and capacity building for gradual IRS formalisation, while supporting the livelihoods of low-income households (Velis et al., 2012). H2020 EWIT is an example of a project for enabling collaboration and knowledge transfer, between the EU and developing economies, regarding plastics flows from WEEE.

Challenges and Knowledge Gaps

Markets for recycled plastics within Europe are underdeveloped. Given this situation, low-quality material in particular is currently uncollected or exported post-collection for recycling (Velis, Lerpiniere & Coronado, 2015; Velis, 2014; Velis C. A., 2015). As seen with the recent Chinese import ban and similar restrictions from ASEAN countries (e.g. Vietnam has issued a temporary import suspension), this leaves Europe vulnerable to disruption. As a consequence, Europe needs to increase its ability to deal with lower-quality recyclates in the short term, and significantly increase its ability to convert larger volumes of after-use plastics to high-quality recyclates in the long term. This requires major investments in collection, sorting and recycling infrastructures, and drastic changes in the design of plastic products (H2020 New_InnoNet). The situation now, however, is that insufficient quantities are collected to begin with, in particular for specialised applications such as electronics (H2020 CloseWEEE). The mechanical recycling sector in the EU is consequently small, with roughly 1 000 firms, mainly SMEs, employing around 30 000 people, so the sector cannot benefit from economies of scale and has limited R&I capabilities (H2020 CLIPP PLUS). Hence, it faces a challenge in scaling up organically and investing in the necessary technology and capacity to increase recycling volumes and quality. In addition, the setup for a well-functioning secondary materials market is insufficient. Acceptance of secondary materials in market outlets in Europe is low, which combined with affordable landfill and low-labour costs outside the EU incentivises exports outside Europe.

It is unclear how much recycled plastic, and what quality grades, the EU industrial sectors are currently able to absorb. Without such an understanding is difficult to develop a common European strategy for infrastructure investments or demand-supply matchmaking. There is no level playing field between EU Member States regarding plastics-related fiscal policy measures, such as the implementation of producer responsibility. This situation creates barriers to the concrete development of the necessary sectors. Combining input streams from different European countries must take into account the fact that legal requirements for waste collection, transport and treatment can differ significantly (H2020 FiberEUse). To grow the market for recycled plastics, active efforts are needed to identify new outputs and applications based on better matching of quality and demand. The EU-wide pledging campaign for the uptake of recycled plastics, as announced in Annex III to the EU Plastics Strategy, is an example of an effort (European Commission, 2018j). Recycling companies today have narrow specifications for input quality (e.g. single-piece, mono-material objects) due to technical and cost limitations, while the constituents of after-use plastics look quite different (FP7 GREEN PACK). There are a number of products and applications where recycled plastics could be used but are currently underutilised (H2020 CloseWEEE). To change the status quo, more transparency and collaboration between stakeholders are critical to enable system-relevant innovation, as are the signals sent by the end-user market (e.g. shoppers and other society stakeholders) with respect to the demand and acceptance of recycled plastics (H2020 New_InnoNet).

Even if scale increases, mechanical recycling faces a cost challenge as long as externalities are not accounted for. Given all the resources needed to generate the secondary resins from after-use plastic products, it remains financially difficult for the waste reprocessing sectors to make recycled plastics both competitive and profitable, despite the gate fees. This can be understood as a market failure as it does not accurately or sufficiently reflect the benefits of the recycling process (H2020 CloseWEEE). Measuring the added benefits (value) in a more holistic, accurate and unambiguous way, incorporating externalities (positive and negative) into the monetary value (pricing) of the secondary plastics is challenging (Millward-Hopkins et al., 2018).

The lack of a coherent regulatory and legislative framework in operation across Europe for different product categories partly prevents uptake of recycled plastics. There are cases, such as the legacy additives in long-life products, where converting companies are still facing legal uncertainty due to the lack of a legislative framework in full operation across Europe (Polymer Comply Europe, 2017). In addition, there is an absence of generally accepted quality standards, adequate monitoring for material flows and collection and recycling definitions. In this regard, the Waste Framework Directive and its 2018 amendment Directive are the relevant pieces of regulation in Europe (European Commission, 2008b and European Commission, 2018h). According to Article 6 of the former, end-of-waste status can be obtained through compliance with an EU regulation for a certain waste type, which exists for instance for scrap metal and glass cullet but not for waste plastics. It can also be obtained at national level, for example through national end-of-waste criteria for waste plastics or company-specific recognitions. However, as identified by the European Commission, the EU's rules on end-of-waste are not fully harmonised, making it uncertain how the waste becomes a new material and product (European Commission, 2018e). Against this background, the Commission, inter alia, is launching a study to gain a better understanding of Member States' practices as regards the implementation and verification of provisions on end-of-waste as a basis for possible guidelines.

Lack of transparency on the quality of recycled input materials is a driver of overengineering. Projects developing recycled plastics with high barrier properties required for food-contact applications experience uncertainty when these materials come from non-authorised recycling processes (FP7 BANUS). Substitution of virgin material with recycled material (e.g. in thermoformed trays, laminated multilayer flexible package and coated paperboard package) poses technical challenges that require innovation to meet the strict barrier standards. There are no suitable tests for realistically assessing set-off, i.e. the transfer of substances from the outer layers of materials and articles to the food-contact side, for example during material storage. This problem holds for both virgin and recycled materials use in FCMs and may lead to overengineering (European Commission, 2006a).

Importing recycled resin from the informal recycling sector gives rise to specific challenges. Such challenges include:

- The need for effective mechanisms to verify that the existing and future quality standards are met by secondary material imports to ensure clean material flows, and to prevent recirculation within the EU of unwanted legacy substances (e.g. POPs) (Hahladakis, Velis, Weber, Iacovidou & Purnell, 2017; Velis, 2014).

- Potential inadvertent competition with IRS production on the global market, which may counteract the aim of attaining the relevant UN SDGs. An unwanted consequence might be partly disabling their potential to mitigate plastic marine litter pollution through the collection of currently uncollected plastic waste (Velis C., 2017; Velis, Lerpiniere & Tsakona, 2017).

- Continued legal and illegal exports to developing economies that might promote sub-optimal IRS sorting without sufficient occupational health and safety protection in place, on top of impeding a level playing field for the EU-based operators, who have to meet relevant standards (Velis, 2014).

Addressing the pricing challenge of virgin versus secondary plastics is a contentious topic. Any potential improvements may require global intergovernmental collaboration – taxation of any kind and the removal or introduction of subsidies will affect entire sectors and national economies. However, major changes in that balance are the fundamental basis for increasing the circularity of after-use resins (Shuaib & Mativenga, 2016). As noted above, some countries such as China have changed the VAT regime for recycled resources.

Determining recycled content and quality comes with several poorly understood challenges. Given the multiplicity of primary plastics, and their transformation during the entire recycling process, the exercise of determining recycled content can become very complex. While BS EN 15343:2007 offers some definitions and procedures, it does not solve the technical challenges of determining the recycled content in practice. More accurate determination of the quality of recycled content creates the confidence to include more of it in new items, but the current level of technological development and understanding not being able to generate the desired level of certainty leads to a chicken-and-egg situation (H2020 New_InnoNet).

Policy recommendations and R&I priorities

Policy recommendations

Set up regulatory and legal frameworks to stimulate the creation of new market outlets, going beyond (food) packaging. Such frameworks could start by focusing on applications with a relatively high share of plastics in the material content, but a comparatively low recycled plastics content. This could be supported by creating standardisation (e.g. voluntary agreements for a recyclability label or for denoting the recycled content used in a product) and structured information exchange mechanisms. Standards should also cover requirements on the safety and technical performance of recycled materials. Exploring ideas about tightening exports and facilitating more economies of scale within the EU, such as a ‘Waste Schengen’ for residual waste transboundary movement between

EU Member States (Arcadis with cooperation from Trinomics, 2016). Regulatory measures such as minimum recycled content would have a direct impact. The legal status of, and end-of-waste criteria for, plastics of industrial or household origin which are collected, sorted, cleaned and in general reclaimed and processed for recycling, should be clarified (Joint Research Centre, European Commission, 2014). At the time of writing, the European Commission was launching a study to gain a better understanding of Member States' practices as regards the implementation and verification of provisions on end-of-waste as a basis for possible guidelines (European Commission, 2018e).

Set up a fiscal framework to level the playing field for the pricing of virgin and recycled materials to spur innovation and to reflect the societal cost of negative externalities, such as greenhouse gas emissions. Secondary materials should deliver a similar performance at a similar or lower price, than the equivalent virgin material. Direct or indirect subsidies for recycled materials would counteract the cost to society of negative externalities of virgin feedstock (e.g. emissions of greenhouse gases), and thus contribute to a low-carbon economy. Such subsidies could be introduced as a VAT reduction, or through EPR schemes with modulated fees for virgin materials. In particular, taxes could be levied on fossil feedstock. Such (in)direct subsidies would support innovation in recycling that has to compete with incumbent virgin production technologies and, for example, currently lacks economies of scale.

Develop and implement standardised methods to verify stated recycled content in plastics. Relevant IT systems and certification schemes may need to be developed. If mandatory use of recycled content is introduced, such a standard is crucial and could potentially be combined with ecodesign guidelines (H2020 New_InnoNet). Similar to methods for verifying bio-based or chemically recycled content, a standardised mass-balance approach could be developed for this purpose.

Create collaboration mechanisms to support industrial symbiosis in order to connect supply and demand of used and recycled plastics. Fully effective cross-sector and cross-value-chain collaboration is critical and needs to be enabled, e.g. through industrial symbiosis. Examples of interventions needed throughout the plastic (packaging) value chain for further closing the loop are being explored and put into practice (KIDV (the Netherlands Institute for Sustainable Packaging), 2017 and Ellen MacArthur Foundation, 2016b).

Change perceptions about the quality and safety of recycled materials through support for design and production, price incentives and clear certification and labelling. Support for design with recycled materials is one example of how to create further uptake (UAntwerp). Commercial examples could also provide inspiration and technical expertise for use of recycled materials, such as the Werner & Mertz cleaner bottle made out of 100 % recycled plastic from the public waste collection system (Werner & Mertz, 2018). The potential need for a cultural shift can be addressed by a certified label that communicates recycled content in packaging and other applications. Such labels can also certify the technical performance of recycled materials. Public health concerns associated with the increased use of recycled content in food-contact applications need be addressed, both at the factual scientific and the perception level. Certification and labelling could help, but need to be part of wider quality assurance and communication efforts.

Develop and implement more holistic methodologies to assess the economic, environmental and social impacts of different pathways for used plastics. The goal should be to establish the benefits beyond energy consumption and GHG emission aspects (Velis & Brunner, 2013; Velis, Lerpiniere & Coronado, 2015 and Hahladakis J. N., Velis, Weber, Iacovidou & Purnell, 2018). Such robust and comprehensive assessment tools should overcome the limitations of current LCA approaches, extending the assessment capabilities to include socioeconomic and technical performance considerations. They also cover all aspects of the value embedded in the after-use materials/components/products, as for example in the case of the 'Complex Value Optimization for Resource Recovery' framework and tool (University of Leeds, 2018; Millward-Hopkins et al., 2018 and Iacovidou et al., 2017).

Set up mechanisms for gathering and sharing information on recycling performance and recycled plastics, in collaboration with international organisations. For example, UN Comtrade could be encouraged to collect international trade data for more major recycled polymers (e.g. PP), which are currently not available (Velis, Lerpiniere & Coronado, 2015).

Provide information for citizens and businesses on the health-related performance of used plastics. Based on available evidence (see Chapter 2), information on the safety aspects of recycled materials should be provided for citizens and business. Technical performance could be reinforced by emphasis and transparency on the decontamination aspects during recycling, which is currently underexplored and poorly documented (Velis & Brunner, 2013). This would, for example, support the use of acquisition agreements as a means of guaranteeing the timely supply of secondary plastics to converters and end users (Deloitte Sustainability, 2017).

Review existing waste legislation to understand the impact delivered and drivers of change. Insights could be extracted, for example, by analysing the impact of the End of Life Vehicles Directive on the non-metallic fraction, and similarly for the Waste Electrical and Electronic Equipment Directive.

R&I priorities

Provide funding for research to understand the dynamics of globalised secondary material supply chains. Understanding the fate of material exported to developing economy countries should be prioritised, in particular traceability and transparency of flows. Other related topics to be investigated include the use of global material trade to ensure minimal environmental, public and occupational health standards at sorting and reprocessing facilities in destination countries.

8 CHEMICAL RECYCLING

To realise the vision of an effective after-use plastics economy, significant improvement is needed in reprocessing methods for plastics so that they can remain in circular pathways. In line with the principles of a circular economy, 'inner loops' are more value preserving since they avoid the economic and environmental cost of breaking down and building up the material structure. Examples of such 'inner loops' are reuse or repair. Similarly, chemical recycling can be considered more as an 'outer loop' because it breaks the material down more than reuse or mechanical recycling. However, chemical recycling could address some limitations present in the inner loops due to mixing, contamination and degradation of the polymers. When assessing the potential of emerging technologies, it is important to understand their technological and economic ability to retain value within current and future markets, in addition to their overall economic, environmental and social impact.

The term 'chemical recycling' is currently used in different ways. In this report it is used to describe any reprocessing technology using chemical agents or processes that directly affect either the formulation of the plastic or the polymer itself. This contrasts with mechanical reprocessing, which only uses physical methods to separate different types of plastics. While other categorisations exist, in this report three main types of chemical recycling are distinguished, which differ significantly in how they work and what outputs they produce (Figure 24).

- **Solvent-based purification** is a process in which the plastic is dissolved in a suitable solvent, in which a series of purification steps are undertaken to separate the polymer from additives and contaminants. The resulting output is the precipitated polymer, which remains unaffected by the process and can be reformulated into plastics[16].

- **Depolymerisation** is the reverse of polymerisation and yields either single monomer molecules or shorter fragments often called oligomers.

- **Feedstock recycling** is any thermal process that converts polymers into simpler molecules. The two main processes here are pyrolysis and gasification.

This chapter discusses all three methods, first addressing solvent-based purification and depolymerisation since they yield outputs that are or can be directly converted into polymer materials. Feedstock recycling stands apart because the outputs are simpler chemicals (e.g. hydrocarbons or syngas), which cannot be directly converted back into plastics but need to be processed in several unit operations to yield a polymer again. While such outputs in theory allow more flexibility, since they can be transformed into many different materials or chemicals using existing manufacturing infrastructure, they are challenging in practice. The main issue, discussed in detail in Section 8.2, is that feedstock recycling outputs can be (and are) used as fuels, which is equivalent to energy recovery and does not contribute to creating a circular economy for plastics. In addition, questions are raised regarding the environmental impact of, for example, energy consumption and treatment of by-products.

Chemical recycling technologies have the potential to bring clear benefits which complement mechanical recycling. However, they should not be perceived as silver-bullet solutions to deal with mixed

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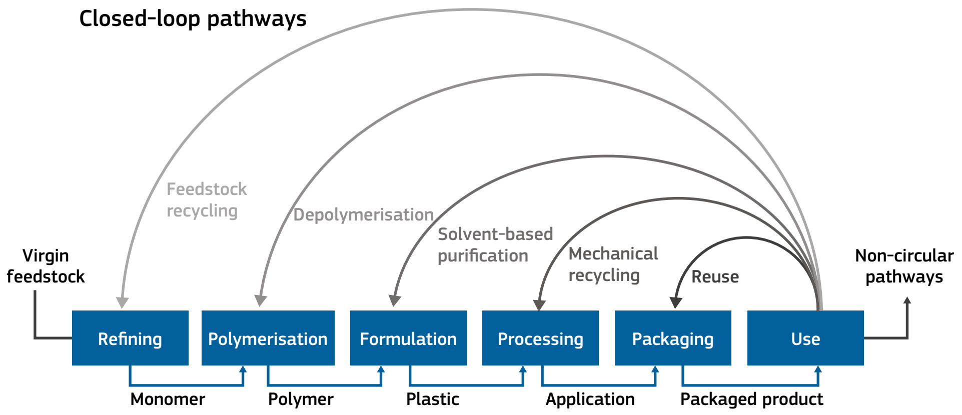
[16] *Since solvent-based purification does not change the constitution of the polymer itself, it has been argued that it should be seen as mechanical rather than chemical recycling, or as a separate class (see also ISO 15270:2008). This report does not take a stance on which option should be preferred. The logic used here is that since chemicals are used in solvent-based purification to change the formulation of the plastic (by removing additives and extracting the base polymer(s)), it can be described as one of several chemical recycling techniques. Note that this positioning of solvent-based purification has been done for practical purposes and does not indicate a recommendation of a standardised terminology.*

Figure 24: **Overview of different loops for plastics in a circular economy**


Closed-loop pathways
Feedstock recycling
Depolymerisation
Solvent-based purification
Mechanical recycling
Reuse
Virgin feedstock
Non-circular pathways
Refining
Polymerisation
Formulation
Processing
Packaging
Use
Monomer
Polymer
Plastic
Application
Packaged product

Source: Drawing by Mats Linder

and contaminated plastics streams. As explained in this report, to achieve the much-needed systemic change, downstream innovation should go hand in hand with upstream solutions that redesign and innovate business models, products and materials.

8.1 Solvent-based purification and depolymerisation technologies

State of Play

Solvent-based purification and depolymerisation result in higher-quality output compared to mechanical recycling because they produce (near) virgin-grade polymers. The main feature of solvent-based purification and depolymerisation is that they transform the used plastics back into purified polymers or monomers. The solvent-purified polymer is ready to be converted into a new plastic product, whereas the monomers from the depolymerisation process must be polymerised again before the material can be converted into a new plastic product. A common denominator is that additives, colourants and contaminants are removed at the molecular level (although contamination can still happen, depending on the setup and rigour of purification and separation processes). While washing, de-inking or other methods can be used to clean the recycled material to some extent, conventional mechanical recycling will always be limited by the input load of additives in plastics. In the case of chemical recycling, such additives and contaminants impact the technologies' performance, but to a lesser extent the output quality.

Solvent-based purification and depolymerisation work differently and are suitable for different plastics according to their chemical properties. Below follows a brief description of each technology and its level of maturity.

Solvent-based purification

Solvent-based purification allows the removal of additives and contaminants, but does not affect the polymer structure. In general, the solvent-based purification works by dissolving the polymer in a specific solvent followed by the removal of contaminants (additives, pigments and NIAS) through filtration or phase extraction, and then precipitating the polymer using an anti-solvent in which the polymer is insoluble. The resulting output is a 'near-virgin' quality, purified polymer that can be reformulated into high-performance applications. The purity of the recycled polymer depends on several process parameters, and there is always the risk of residual contaminants because of variations in input that go beyond what a given solvent-based purification process was designed for. Because the purification process does not change the polymer itself, the dispersity due to mixing of different polymer grades (e.g. different polymer chain lengths or levels of branching) remains more or less the same. In addition, since any mechanical conversion of a resin to form a plastic object (e.g. extrusion and blow moulding) brings physical and thermal stress that decreases the average chain length, solvent-based purification is not a 'perpetual' recycling method for plastics. There is also the risk of residual additives or solvent that were not removed during the process, which might impact the material quality. In other words, if a polymer was to go through consecutive cycles of purification, the mechanical reprocessing would eventually wear it down. In both these aspects, solvent-based purification is akin to mechanical recycling.

So far, solvent-based recycling for packaging does not exist at scale. Commercial scale solvent-based purification of PVC has existed since 2002, when the joint venture VinyLoop set up a 10 000 tonnes/year plant in Italy. However, it was announced in June 2018 that the PVC recycling would be discontinued (Vinyloop). It has been demonstrated that purification processes of PS and PC based on solvent purification techniques are able to remove additives and thus produce polymers with a quality similar to virgin (FP7 POLYSOLVE). For PS, solvent-based purification has in part been driven by the need to remove the brominated flame retardant hexabromocyclododecane (HBCD) from old insulation material for reuse or destruction, a process which also yields the purified polymer (Schlummer et al., 2017). In 2017, the EU-funded cooperative PolyStyreneLoop was created with the aim of recycling PS across Europe using the CreaSolv® Process (see also below PolyStryeneLoop). Polyolefins such as PE and PP can be solvent-purified at high temperature and pressure (PureCycle Technologies). This kind of technology could open the way to chemically recycling the first and the second most used plastics, together representing more than 50 % of polymer production volume globally. In packaging, Unilever is currently piloting the CreaSolv® process in Indonesia, predominantly to recover PE from multi-material sachets (Unilever, 2017). In the US, P&G has partnered with PureCycle Technologies to pilot a similar method for purifying PP for use in home cleaning and hygiene product packaging (PR Newswire, 2017). In Europe, APK Aluminium und Kunststoffe is working on recycling several polymers (notably from multilayer packaging) with its Newcycling® technology.

While solvent-based purification is technically able to separate complex layers of plastics into pure recyclates, its practical feasibility remains unclear. Using solvent-based purification for packaging recycling is still a relatively new idea, and questions remain about the economic window of viability. As evidenced by the more mature processes (e.g. PVC and PS recycling), commercial focus has so far been directed at more homogenous bulk materials, and even that has proven challenging. The idea that the technology could be a pathway to separating different components in a multi-material laminate is appealing, but this would require additional steps of solvation and separation. One key issue is the time and energy input needed for solvent removal, making economies of scale challenging (Kasier, Schmid & Schlummer, 2018). In addition, questions remain on the impact of the solvent on the recycled material, e.g. traces of the solvent left in the output polymer, and on the processing of the left-over solvent, potentially contaminated with plastic additives and contaminants.

Depolymerisation of polycondensates

Polycondensates, which include polyesters and polyamides, are well-suited for depolymerisation (H2020 DEMETO; Carbios; Ioniqa; ECONYL and Aguado, Martinez, Moral, Fermoso & Irusta, 2011). The group of polycondensates contain, amongst other polymers, PET, PA, PU (sometimes denoted as PUR) and bio-based polymers such as PLA, PHAs and PEF, which all essentially lend themselves to depolymerisation. They share the property that their polymerisation is a so-called condensation reaction, where forming the chemical bond holding together two fragments is accompanied by 'condensing' them and knocking out a solvent molecule, such as H_2O. These bonds are typically ester bonds as in PET, carbamate bonds as in PU, or amide bonds as in PAs. Condensation reactions are reversible. Hence, the right reaction conditions to push the thermodynamic equilibrium in the reverse direction, together with a suitable catalyst, can break the ester/carbamate /amide bonds. In particular, the bonds can be broken exactly where they were formed and 'add back' the solvent molecule to return it to the starting material. For processing reasons, one might prefer not to produce the pure monomers again, but rather fragments, such as dimers or oligomers. These are already pre-organised for making a new polymer at the expense of losing some flexibility, such as using the mono ethylene glycol monomers for purposes other than producing PET.

Since the depolymerisation reaction breaks up the polymer into its original building blocks, they can be used, separately or together with virgin monomer, to make new virgin-grade polymers. The same chemical processes can be used as for manufacturing polycondensate polymers from virgin feedstock. A notable consequence is that depolymerisation enables the same flexibility with respect to polymer quality and grades as virgin production. The output is, in principle, not dependent on the mix of different PET polymer grades. This would overcome the limitation in mechanical recycling that even pure rPET is a mix of polymers of slightly different composition, which affects quality. The recycled monomer can be used to manufacture whichever version of the polymer the market demands. In addition, depolymerisation enables recycling of polymers between different value chains, with PET in packaging and textiles as the prime example. Synthetic fibres – in which PET is commonly referred to as polyester – account for more than 60 % of the PET production, while food packaging accounts for most of the remaining volume. Both applications use mechanically recycled resin but to date, material flows are mostly one way. In fact, except for some applications such as bottle-to-bottle recycling, most mechanically recycled packaging PET is used in lower-value packaging or for making polyester yarn. Regarding textiles, less than 1 % of the material used to produce clothing is recycled into new clothing (Ellen MacArthur Foundation, 2017). Clearly, such a cascading pattern is insufficient to create circular material flows. Depolymerisation could be the preferred recycling technology for synthetic textiles, especially for materials of such low quality that there are no other viable recycling alternatives.

PET is the most widely researched polymer for depolymerisation. As PET is the highest volume polycondensate on the market, accounting for 18 % of global plastic production, it is not surprising that depolymerisation of this polymer has received significant attention from industry (Mouzakis, 2012). PET can be depolymerised using chemical catalysts or via enzymatic reactions, and several processes have been proposed in an industrial context, while most are still at laboratory level (Carbios, 2018; Austin et al., 2018; H2020 DEMETO and Ioniqa). Several early-stage industrial pilots exist to depolymerise PET, or polyester as it is commonly referred to when talking about fibres, both from packaging and textiles. Examples of companies or projects that have reached industrial-pilot level include gr3n, which is part of the consortium DEMETO (H2020 DEMETO), Loop Industries, Ioniqa and perPETual Global Technologies. PU/PURs are collectively the fifth most produced plastics in the world, but their chemical recycling trough depolymerisation is at the moment confined to research level (Aguado, Martinez, Moral, Fermoso & Irusta, 2011). Depolymerisation for PA, ranking ninth in European production (PlasticsEurope, 2018), is on the market. The technology is mainly used to treat off-spec material inside production facilities for carpets and other nylon-based textiles. For example, Aquafil uses depolymerisation to turn used nylon, i.e. a brand of PA, into ECONYL yarn. Most depolymerisation technologies involve high costs due to energy intensity and decontamination.

In the Aquafil case, this can be partly counterbalanced by the high price of virgin PA, compared to PET or polyolefins, and by adding value through selling yarns instead of raw material (ECONYL, 2018).

The energy required for chain cleavage and recovering the monomer depend on the polymer, the reaction pathway and specific separation process. The higher production costs of the new polymers, compared to large-scale virgin polymer production, are a key barrier to overcome. As early-stage estimates of depolymerisation's GWP look promising, compared to virgin polymers, they could be a levelling factor. To estimate the environmental impact of depolymerisation, the production of a new polymer using recycled monomers and fossil-based monomers is compared, most often using the metric of GWP. The GWP of PET made from recycled monomer is estimated to be ~60% of virgin fossil-based PET, while the GWP of chemically recycled PA6 is ~36% of the virgin, fossil-based counterpart – twice not taking into account the additional benefit of recycling the monomer again (H2020 DEMETO). For PU/PURs no GWP data are currently available. Less information is available on other environmental and systemic impacts of depolymerisation, such as leftover by-products or chemical safety of the catalysts' use.

Depolymerisation of other materials

Poly(methyl methacrylate) (PMMA), also known as acrylic, and PS need to be mentioned as special cases of depolymerisation of non-polycondensates. At least at research level, it is demonstrated that PMMA can be depolymerised into monomers with high yield when it ispyrolysed under controlled conditions (Lopez et al., 2010). This is a peculiar case because usually pyrolysis produces a distribution of different (non-monomer) molecules and not a specific product with narrow specifications (pyrolysis is described in detail in Section 8.2). Several companies, such as Agilyx and Polystyvert, market processes for PS depolymerisation, although mainly for bulk applications such as insulation material. In 2018, ReVital Polymers, Pyrowave and INEOS Styrolution launched a consortium to recycle single-use PS packaging through catalytic microwave depolymerisation technology (Plastics in Packaging, 2018). Other suggested methods for depolymerising polyolefins, for example through metathesis, are in the very early development stages with challenges and concerns similar to those discussed for feedstock recycling (see Section 8.2) (Jia, Qin, Friedberger, Guan & Huang, 2016).

Challenges and knowledge gaps

To date, there is limited evidence that the different chemical recycling technologies for PET, PE, PP, PMMA and PS will be competitive at industrial level in current market conditions. These polymers, together representing more than 70% of global production, are commodities implying that the price competition with virgin polymers is a clear bottleneck for both solvent-based purification and depolymerisation. This bottleneck can be further broken down into a number of technical and structural challenges.

Chemical recycling technologies still need significant development to mature. With one of the few commercial processes (solvent-based PVC purification) recently shut down and most initiatives outlined above at lab scale or pilot level, it is evident that more resources and time investment are needed to improve the technologies. Factors such as yield and energy efficiency affect the cost, as any conversion of a material requires energy. The energy sources as well as the amount used is crucial for the overall effectiveness of chemical recycling. Another example is the challenge of solvent-trace removal for solvent-based purification (FP7 POLY-SOLVE).

Environmental and social impacts of chemical recycling need to be evaluated at the industrial level. If more was known about the potential positive impacts at scale as well as possible unintended consequences, it could incentivise more investment and support. However, such knowledge still does not exist. An added complication is that current methodologies and tools for assessing and comparing the environmental and social impact of recycling technologies are not sufficiently adapted to deal with chemical recycling.

As for mechanical recycling, infrastructure and transport costs are challenging as plastics are lightweight and production volumes need to be high. Transporting plastics long distances is costly and places a limit on how large or centralised recycling plants can be. (Expanded) polystyrene ((E) PS) is a particularly challenging case in point, as polystyrene accounts for only 2 % of the volume of uncompacted EPS foams (Rubio, 2018). At the same time, the output of chemical recycling operations – polymer resin or virgin monomer – are typically processed in large-scale facilities. If the chemical recycling plants were forced to be more spread out geographically, they would face the challenge of the high transport costs of getting their output to their customers.

Policy Recommendations and R&I priorities

Policy recommendations

Review and update waste legislation to include the latest recycling technologies, ensuring consistency across policy initiatives. This adaptation should also cover standardised definitions and legal status (e.g. through end-of-waste criteria) to provide clarity on the nature and output of the technologies in scope, as well as on how they relate to other technologies in the waste hierarchy (see also (Joint Research Centre, European Commission, 2014)). The Commission is launching a study, with deliverables scheduled for 2019, to ascertain a legal framework and practices in Member States, to identify end-of-waste applications (best and sub-optimal), and to provide recommendations on the design of national legal and enforcement regimes for end-of-waste (as of November 2018). Member States are also looking into this, with, for example, the Netherlands differentiating based on the potential applications of the output (Rijkswaterstaat, Ministry of Infrastructure and Water Management, 2017). Consistency between policy initiatives should reinforce different measures and mitigate the risk of additional barriers, such as cross-border transportation. For example, incentives for energy recovery through incineration of plastic waste should not hamper efforts on prevention or recycling.

Develop and implement standards for quality of recycled plastics. Valorisation of chemical recycling technologies in terms of better properties of the recycled material compared to mechanical recycling is needed to ensure scaling up. With this in mind, recognition of the added value of chemical recycling compared to mechanical recycling should be clarified. Such standards could be linked to the development of tradable certificates that prove that certain plastics are recycled or generated using recycled or renewable content, and possibly renewable energy.

Develop a fiscal framework to account for the cost of negative externalities related to different pathways for processing used plastics. Being commodities, the most common plastics have costs driven by supply-demand mechanisms and scale. However, the current system fails to account for the externalised cost of production and use (United Nations Environment Programme, 2014). The collection, sorting and recycling costs are then usually paid by society, i.e. citizens. When companies bear no responsibility for these costs, the brands' choices are driven only by the cost of the virgin-fossil-based plastics, which is effectively discounted compared to that of (chemically) recycled plastics. Since quality and performance are on a par, the market opts for the less expensive (discounted) option. This mechanism blocks the promotion of a circular economy and finally the innovation enabling the solvent-based purification and depolymerisation. Consequently, providing a framework to level the playing field is needed to enable these technologies to become commercially viable. This overarching need can be broken down into a number of policy options:

Provide a fiscal framework to account for the costs of negative externalities due to the use of virgin (fossil-based) feedstock. For example, to fill the cost gap between virgin plastics and mechanically/chemically recycled plastics, a fee for the former would support the uptake of the latter. The money collected from the producers could be earmarked for improving the quantity and quality of recycled plastics. Both the EU and several Member States have already expressed thoughts on taxing non-recycled plastic packaging.

R&I priorities

Provide financial incentives for innovation to redesign products and materials that improve the efficiency and effectiveness of mechanical and chemical recycling. Many design improvements are relevant for improving both mechanical and chemical recycling, such as avoiding certain additives or combining different materials. Specific (re)design measures for chemical recycling include, for example, avoiding the presence of two different depolymerisable polymers, or of two polymers soluble in the same solvent when the solvent-based purification is the final recycling destination of that specific product. In a longer perspective, if industry-scale solvent-based purification and depolymerisation were in place to complement mechanical recycling, the use of non-chemically recyclable materials would be discouraged.

Provide funding for industrial piloting of solvent-based purification and depolymerisation. As a first step, fund industrial pilot plants for depolymerisation with a process capacity of 1 000 tonnes per year. A plant with such a capacity should be enough to assess the economic, environmental and social impacts of the technologies. At the same time, it could provide enough material for the plastic converters to assess the performance for different applications, as these technologies will not take off without industrial validation. Pilots should also provide insights into the environmental and social impacts of, for example, processing the waste output, or of traces of solvents in the recycled material.

Provide funding for research to develop PMMA monomerisation and solvent-based purification of PS and PC. This should happen through collaboration between academia, public research institutes and industry.

8.2 Feedstock recycling technologies

State of Play

Pyrolysis and gasification transform plastics and most of its additives and contaminants into basic chemicals. These technologies are based on heating up the plastics in an atmosphere of no (pyrolysis) or limited (gasification) oxygen content. Because the output in both cases are molecules that cannot be directly converted into polymers but need to be used as feedstock in a refining-conversion-polymerisation process, they are classified as feedstock recycling in this report.

Pyrolysis

In pyrolysis, plastics are broken down into a range of simpler hydrocarbon compounds. The word ‘pyrolysis’ comes from the Greek for ‘breaking’ (*lysis*) and ‘fire’ (*pyro*). It is a generic name for all thermochemical operations involving heating in the absence of oxygen. Since most polyolefins degrade spontaneously at only a few hundred degrees Celsius, adding heat alone is enough to break them down into smaller fragments. In the absence of oxygen, the polymers tend to fragment into smaller hydrocarbon molecules, which can be collected as an effluent by condensing the hot gases. However, the degradation is not controllable in the same way as depolymerisation is. Instead, bond cleavage happens in random positions, leading to a distribution of output molecular weights and structures. It typically includes heavier, waxy fragments as well as very light (C2-C4) fragments which can be separated in the condensation step. Such a hydrocarbon mix resembles the composition of oil and can be used directly as a fuel (Onwudili, Insura & Williams, 2009). As described in the previous section, an exception to this rule is the pyrolysis of PMMA and PS, which can be used, in very controlled conditions, to produce monomers (Aguado, Olazar, Gaisán, Prieto & Bilbao, 2003). The exact composition of the hydrocarbon mix can be controlled to some extent by varying the process parameters (e.g. operational temperature, retention time, separation and reflux).

Industry-scale pyrolysis has failed in the past, but new pilots are emerging. In the past, pyrolysis for material recycling was tried but discontinued several times due to the challenging economics (TNO Institute of Strategy, Technology and Policy, 1999). More recently however, both large and small industrial players have proposed new or modified pyrolysis processes (letsrecycle.com, 2018 and SABIC, 2018). One example is the UK start-up Recycling Technologies, which uses a fluidised bed reactor to distribute temperature evenly. As a result, the equipment can be kept small and modularised, which is potentially more adapted to a dispersed collection and recycling system for plastics (Recycling Technologies).

If the output of pyrolysis were to be used to successfully make new materials at scale, the impact on plastics recycling could be profound because it could pave the way to the chemical recycling of polyolefins. The output of pyrolysis can be processed much in the same way as oil, using conventional refining technologies to produce value-added chemicals, including building blocks for polymers. Thus, while pyrolysis itself is not a sufficient unit operation to chemically recycle the polymers back to materials, the additional processing infrastructure needed already exists in a mature and efficient value chain. Since polyolefins (PE and PP) are the most used polymers by volume, representing roughly half of the plastic consumed by EU converters, using pyrolysis followed by conventional refining could fill a large process gap as they cannot be depolymerised directly back into monomer (ethylene and propylene) (PlasticsEurope, 2018). Thus, if the output from pyrolysis were to be refined into new ethylene or propylene monomer, rather than a fuel, new polyolefins could be made from this recycled feedstock. Since they would be indistinguishable from virgin-grade polymers, like recycled polymers made from depolymerisation (described in Section 8.1), it would be possible to significantly increase the recycled content in plastics without negatively affecting the material quality or safety. Similar to solvent-based purification and depolymerisation, pyrolysis can clean out additives and contaminants as part of the process. This happens by either converting (organic) additives into hydrocarbons as well or separating out solid-state waste materials at the back-end of the process.

Another advantage of pyrolysis is its robustness and flexibility in terms of feedstock. Because the process is thermal and will break down different polymers and other organic materials in an analogous way, the process can be applied to mixed and contaminated plastics streams, and also to vulcanised polymers such as rubber used for tyres in the automotive industry, which currently cannot be recycled in other ways (Williams, 2013). Being able to recycle highly mixed or contaminated after-use plastics could be a key complementary technology to conventional collection, sorting and mechanical recycling, where the quality achieved is limited despite having the potential to improve significantly.

Pyrolysis has known shortcomings, such as high energy requirements, additional refining and output contaminants. Other chemical recycling methods, such as solvent-based purification and depolymerisation, typically require significant energy input. However, the output of pyrolysis requires additional energy-consuming steps to refine into a polymer again. The energy required to conduct the heating is roughly 5-20% of the calorific value of the total input, putting an upper limit on the total recycling yield unless some external energy source is used (Aguado, Olazar, Gaisán, Prieto & Bilbao, 2003 and Westerhout, Waanders, Kuipers & van Swaaij, 1997). As a result, incentives to use pyrolysis to convert plastics into feedstock for new materials are low if there is no explicit demand for recycled materials or content. In addition, when using mixed and contaminated plastics as input, the pyrolysis process produces a mix of chemicals which may need to be purified since the combination of input mix and process parameters can lead to the formation of hazardous chemicals such as PAHs or dioxins. The latter happens if residual PVC or other chlorinated compounds are not removed from the input stream. If that is the case, additional treatment is needed for the effluent or fumes to eliminate the hazardous compounds. It should be mentioned that ongoing improvements are reducing energy demand, and alternative methods, such as catalytic cracking and hydrocracking, could increase the output specificity and reduce contaminant production, while potentially being less energy-demanding (Garforth, Ali & Hernández-Martínez, 2004). However, such methods require catalysts and/or a more sophisticated process setup.

From a systems point of view, there is a risk that a 'plastics-to-fuel' pathway will be preferred by the market, creating a 'linear lock-in' for plastics. As feedstock recyclers seek to find a market for their pyrolysis output, they may opt for selling it as fuel, e.g. in the form of crude diesel for power plants or ships. This is currently the main viable market for pyrolysis output, apart from a smaller portion of the heavier fragments which can be sold as waxes, grease and similar chemicals. From an economic angle, the challenge in converting the output of future pyrolysis units into materials instead, may lie in the difference in scale. The throughput of the petrochemical industry dwarfs that of the first attempts at industrial-level pyrolysis, making it difficult to sell the relatively small volumes produced to a suitable refinery. This chicken-or-egg dilemma can be compared to that of introducing chemicals from renewable feedstock to the market (see Chapter 4). As a consequence, there is significant uncertainty about whether building a pyrolysis infrastructure to recycle plastics will actually lead to new materials, or only to fuels. Such a linear lock-in is clearly not in line with the basic principles of a circular economy and is one of the major concerns when considering the role of pyrolysis in the plastics economy.

Investments in a pyrolysis infrastructure would take several years to become viable at scale. In this way, if the technology invested in does not allow for plastics-to-plastics recycling, the infrastructure lock-in would prevent further innovation and investment in future-proof technologies. This outcome would be reinforced if the sub-optimal technology is perceived as a silver-bullet solution for dealing with mixed and contaminated plastics streams. In that case, the sense of urgency, and the related incentives to redesign and innovate products and materials upstream would be reduced, hindering the transitioning towards a circular economy for plastics.

Gasification

Gasification is less sensitive to the input quality than pyrolysis but it requires more energy and large-scale operations. Gasification is a process where mixed after-use materials are heated (~1 000 - 1 500' °C) in the presence of limited oxygen to produce syngas (a mix of predominantly hydrogen and carbon monoxide). The syngas can then be used to produce a variety of chemicals and plastics, for example via methanol or ammonia, both versatile platform chemicals (Antonetti et al., 2017). The high-temperature requirement means that gasification is energy-intensive and depends on the construction of sufficiently large processing units to be viable. Historically, such units have taken mixed waste input to secure a sufficient volume. This can be seen as an advantage (the ability to process mixed waste places less pressure on the collection and sorting system), but is at the same time poorly aligned with the ambition to separately collect and sort after-use plastics. Moreover, gasification typically needs pre-treatment to remove moisture and increase the calorific value to 14-18 MJ/kg to be energy efficient enough, with the resulting cost increasing with the amount of household waste included in the mix (Expert interviews, 2018).

Though versatile, the output chemicals are in scope for producing fuels and fertiliser, creating a risk of a linear lock-in for plastics. While the versatility of producing syngas and its derivatives from gasification can be seen as an advantage, there is a high likelihood that the output products would be used as fuel, as is the case nowadays. As with pyrolysis, further processing costs more and requires the necessary infrastructure nearby, and at the moment the conversion of methanol to for example polymer precursors is only practiced in China, due to its extensive coal gasification and lack of its own oil resources. At the same time, incentive systems to produce bio-methanol also reward waste-derived methanol. Ammonia can be used to produce fertiliser that could displace fossil-derived fertilisers (Antonetti et al., 2017). However, if the input for the gasification came from fossil-derived plastics or other finite materials, the result would be a linear lock-in as in the plastics-to-fuel case.

Challenges and knowledge gaps

The low cost of oil and gas, combined with the comparatively high costs of feedstock recycling (partly driven by energy demand), makes it difficult to compete with virgin fossil feedstock. Such a competitive disadvantage raises questions about whether there will be demand for plastics made from recycled feedstock, and thwarts investment in industrial piloting and scale-up. Since using the output as fuel requires much less processing, there is a risk that it will be preferred as the most cost-efficient option based on the capacity that is built.

Given the existing petrochemical infrastructure, it is challenging to tweak current pyrolysis output to produce refined chemicals in a cost-efficient way. In order to convert pyrolysis output to plastics, it would be desirable to maximise the naphtha fraction, which is technically difficult and may require longer, more expensive retention times. While it is possible to convert lighter and heavier fractions into the desired molecules, the technical and economic feasibility of doing so remains to be proven. Additionally, the lack of incentives for chemical producers to buy geographically dispersed and relatively small volumes of chemically recycled feedstock is a barrier.

Current methodologies and tools for assessing and comparing the environmental and social impacts of recycling technologies are not sufficiently adapted to dealing with feedstock recycling. An industrial assessment framework that could be applied to feedstock recycling (as well as other chemical recycling methods) and balance the (potentially) added costs against other benefits, would create transparency to help stakeholders select between different options, and account for environmental savings. In addition, an appropriate assessment would be helpful in guiding policy directed at incentivising systemic solution. While some methodologies exist, such as LCA tools, they are insufficiently adapted to the systemic approach of a circular economy (see Section 5.2).

A standard way of accounting for recycled content in chemicals produced through feedstock recycling is lacking. Depolymerisation and solvent-based purification reintroduce the feedstock into the plastics cycle directly, which makes it more straightforward to compute how much of a material is made up of recycled content. Pyrolysis and gasification though, transform it into other chemicals, which require several unit operations to be transformed into polymers again – and might be used to make other chemicals. Since such processes take place in large complex plants, it is impossible to keep track of the exact destiny of the chemically recycled molecules and a mass-balance approach would be needed. While several stakeholders are exploring how mass-balance accounting could work, there is currently no real standardisation effort.

Policy Recommendations and R&I priorities

Policy recommendations

Develop a holistic method to assess and calculate the environmental impact of recycled materials for different recycling pathways (mechanical, chemical, feedstock and organic). In order to clarify the role different after-use recycling pathways could play in a circular economy, more knowledge is needed on their economic, environmental and social impacts. Such an assessment would need to be based on a standardised methodology and guided by the principles of the circular economy and waste hierarchy.

Develop and implement a standard to verify recycled content in materials manufactured in chemical processes. This could for example be based on a mass-balance approach. This work should include the development of a process to certify whether the chemical recycling output is used for new materials, or as fuel. Such a formal certification could boost investment in chemical recycling into new materials, as they would contribute to recycling targets and support voluntary commitments by brands.

Develop and implement a framework to assess the potential role of feedstock recycling technologies. Such a framework could help in understanding the potential contribution of these technologies to recycling targets. Because pyrolysis and gasification are able to treat mixed and contaminated plastic material streams and convert them into basic chemicals, it is important to investigate if and how they could complement mechanical recycling, solvent-based purification and depolymerisation for materials which are too mixed or contaminated to be processed in other ways.

R&I priorities

Provide funding to verify the economic and environmental impacts of feedstock recycling for industrial application through pilots and collaborative efforts. The verification should be based on a set of realistic boundary conditions, and allow comparison with other after-use pathways.

8.3 The role of chemical recycling in a circular economy for plastics

State of Play

The development of chemical recycling technologies is motivated by the need to process materials difficult to treat with mechanical recycling, and to produce recycled materials of higher quality. In order to evaluate the role of chemical recycling, its potential should be considered in the context of mechanical recycling, the only widespread plastics recycling method currently available on the market. As shown above, both solvent-based purification and depolymerisation can complement mechanical recycling in two main ways:

- **Removal of additives and contaminants.** Mechanical recycling cannot efficiently remove additives and contaminants from plastics. Due to the mixing of many additives and contaminants, knowledge about the composition of the recycled material is lost, and with that a large portion of its value – notably the possibility of using it in food-grade applications. As a consequence, landfill and energy recovery are currently the only economically feasible options for treating after-use plastics in many regions. In countries where landfill restrictions have been introduced, recycling of household plastics has increased. However, simultaneously the thermal energy recovery rate is higher in these countries than the rates in countries without any landfill limitations (PlasticsEurope, 2018). While changes in design and material choices (see Chapter 5) can significantly improve the viability of mechanical recycling, quality losses are still expected as long as there are additives and pigments. Chemical recycling is able to process such material as they 'clean' the material at molecular level. Such an approach is for example demonstrated in the FP7 POLY-SOLVE project, where flame retardants are removed from the polymer (FP7 POLY-SOLVE).

- **Repurposing chemical building blocks to (near) virgin quality.** Since all unit operations used to convert a resin into a plastic item gradually wears down the polymer, only relying on mechanical recycling has the limitation that it cannot fully replenish the materials in the system. In addition, the diversity of polymer grades on the market means that the integrity of a recycled resin will always be lower than that of virgin resins, whose properties are fully controlled by the manufacturer. Depolymerisation offers a pathway around these constraints.

Chemical recycling would support achieving the EU's targets on recycling levels but is far from being implemented at scale. Chemical recycling can play a role in a circular economy for plastics, as it can address contamination, mixing and gradual degradation. In this way, these recycling technologies offer important pathways to achieving both higher volumes and higher quality of reprocessed materials. However, since none of the technologies described in this chapter exist at scale yet, the question arises as to how to support their development while working collaboratively to build a functioning system and avoid unintended consequences.

Market signals have started to emerge about the increasing demand for recycled content in plastics, potentially creating more favourable conditions for chemical recycling in the future. The recent increase in awareness and global momentum towards tackling plastic waste and pollution has led to businesses communicating that they intend to increase the share of recycled content in their product portfolios. Since chemical recycling offers high rates (up to 100 %) of recycled content without diminishing quality, there may be increased demand for such materials, which would act as signal to invest in more capacity.

Challenges or Knowledge Gaps

There is no EU-wide vision of a holistic recycling system that incorporates chemical alongside mechanical recycling. There is no obvious answer as to how much capacity is needed for the different forms of chemical recycling, and how they influence the required capacity for sorting and mechanical recycling. While one could argue that market forces should decide, such an approach could have unintended consequences. If different chemical recycling technologies were all to be implemented at scale alongside existing recycling infrastructure, the system would significantly increase its after-use pathways, as well as the multiple combinations of material flows between them (e.g. residuals from mechanical recycling going to feedstock recycling), which could lead to increased resilience. Another possible scenario is that the market converges towards simple, catch-all solutions (i.e. feedstock recycling), rendering mechanical recycling unviable with stranded assets as a result. While it is unclear how the after-use system will evolve, creating a vision for what a holistic after-use system in the EU could look like, and how chemical recycling should be incorporated, is crucial. While an EU-wide vision is lacking, some initiatives are developing a local vision.

With low fossil fuel prices, it is questionable whether chemical recycling can be competitive on its own. Chemical recycling is costly due to its intensive use of energy and other operational costs. While chemically recycled plastics could command a premium compared to mechanically recycled materials due to their higher quality, they are still only on a par with virgin materials. As long as the latter are cheap to produce, due to low fossil fuel prices and large-scale production, it would be difficult for chemically recycled plastics to compete on price only.

Even with early signals of increasing demand, uncertainty about the future prevents investment in new capacity. Since chemical processes often involve significant investment and need to reach an appreciable scale to make economic sense, confidence in future demand (as well as price) is crucial to enabling investment in building new capacity. Despite recent global momentum, uncertainty still prevails and limits planning and investment.

Policy Recommendations and R&I priorities

Policy recommendations

Develop a vision for a holistic recycling system in Europe, incorporating chemical recycling. Such a vision should clearly describe how scaling up these new technologies would enable the EU to reach its recycling targets, as well as create a virtuous circle where higher-quality recycled materials lead to further increases in recycled content in plastics.

Review and update waste legislation to include the latest recycling technologies. This adaptation should include the implementation of technical standards to ensure virgin-grade recycled polymers can be used in the same applications as corresponding virgin polymers. It should also cover standardised definitions and legal status (e.g. through end-of-waste criteria) to provide clarity on the nature and output of the technologies in scope, as well as on how they relate to other technologies in the waste hierarchy (see also Joint Research Centre, European Commission, 2014). The Commission is launching a study, with deliverables scheduled for summer 2019, to ascertain a legal framework and practices in Member States, to identify end-of-waste applications (best and sub-optimal), and to provide recommendations on the design of national legal and enforcement regimes for end-of-waste (as of November 2018).

Set regulatory and/or fiscal measures to boost the use of recycled content. Fiscal incentives could include reduced VAT or lowered EPR fees, and regulatory measures could include a time-bound target for specific rates of recycled content. Such measures could include setting up a kind of trading scheme for recycling (and reuse) credits, comparable to the emissions trading scheme (ETS). Lessons can be learned from ETS to ensure incentives are not skewed. Measures need to be harmonised with planned or anticipated expansion of mechanical and chemical recycling capacity.

9 ORGANIC RECYCLING AND BIODEGRADATION

While conventional plastics typically last for decades or even centuries, polymers exist that can biodegrade in a much shorter timeframe. Such compostable or biodegradable plastics enable alternative after-use pathways, such as industrial composting. These properties can bring benefits such as the ability to process items which, due to their complexity or specific use scenario, are hard to reuse or recycle, as well as generate added-value products. However, there are still challenges in ensuring their beneficial use at scale. This might explain why a significant market breakthrough has not yet taken place, although compostable and biodegradable plastics have been on the market for more than 25 years.

9.1 Biodegradation under controlled conditions

State of Play

Biodegradation under controlled conditions, such as organic recycling, fits into a circular economy through the idea of closing the biological cycle, if biological feedstock is used (World Economic Forum, Ellen MacArthur Foundation and McKinsey & Company, 2016)[17]. The organic component is recycled in a way that mimics nature. A major part of the material is turned into CO_2, and the remaining mineral component, including nutrients, is recycled back into compost (i.e. humus), which can be used to enhance the quality of the soil. Note that the CO_2 produced from bio-based materials is 'short-cycle carbon', which was absorbed into biomass relatively recently, as opposed to fossil feedstock. Therefore, in this sense, this process does not add net CO_2 to the atmosphere provided the natural capital is managed well globally (disregarding emissions generated through farming, transport and conversion). For similar reasons, this is not the case for compostable plastics made from polymers derived from fossil feedstock. Currently, about 24 % of all compostable plastics on the market are fossil-based (nova Institute, 2017). Compostable polymers often contain some share of fossil-feedstock-based polymer to provide the specific technical characteristics required, but there is ongoing research to produce polymers with similar properties from renewable resources.

While the term 'compostable plastics' is commonly used, nuances are needed to reflect the behaviour of compostable plastics in practice. In general, 'compostable' is used to indicate that materials biodegrade sufficiently quickly in a composting environment with no adverse effects on the quality of the compost. If the compostable material is collected, a related term is biological waste treatment or organic recycling, which besides aerobic industrial composting, also includes anaerobic digestion (AD; sometimes referred to as biogasification). In the latter process, organic matter is broken down by a microbial population of bacteria in the absence of oxygen (anaerobically). Composting can be subdivided into industrial composting (once the material has been collected, and thus centralised) and home composting (see Figure 25)[18]. These nuances are important since environmental conditions differ between these options and therefore also the resulting properties of the compostable materials. Some of these differences can be attributed to the role of fungi and temperature in the biodegradation process, while others result from the nature of the polymer and the way the biological treatment proceeds. Furthermore,

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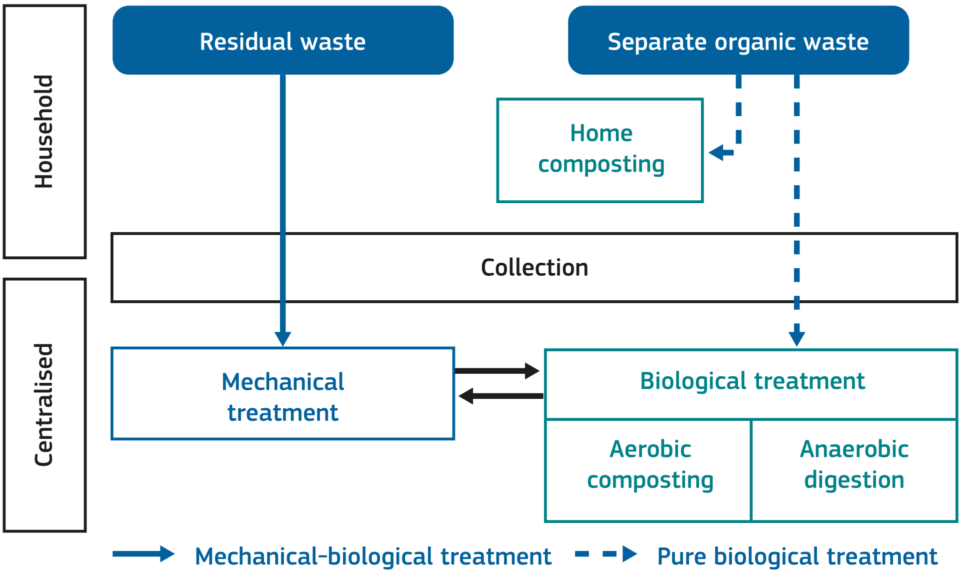
[17] *'Organic recycling' is defined by the EU Packaging and Packaging Waste Directive 94/62/EC (amended in 2005/20/EC) as the aerobic (composting) or anaerobic (biomethanisation) treatment, under controlled conditions and using microorganisms, of the biodegradable parts of packaging waste, which produces stabilised organic residues or methane.*

[18] *Strictly applying the definition given in the PPWD, home composting is not a form of organic recycling, as conditions are not controlled. Moreover, some consider home composting as a form of waste reduction (rather than recycling), since the organic matter does not enter the formal waste management system. In this chapter, we will take a more technical perspective, and consider home composting, if done properly, to be a form of organic recycling.*

Figure 25: Schematic overview of different options for biological waste treatment


Household
Centralised
Residual waste
Separate organic waste
Home composting
Collection
Mechanical treatment
Biological treatment
Aerobic composting
Anaerobic digestion
Mechanical-biological treatment
Pure biological treatment

Source: FP7 OPEN-BIO

organic waste can be collected separately prior to biological treatment in order to achieve a better quality of compost. If separate collection is not taking place, biological treatment is mostly combined with a thorough mechanical treatment of the mixed residual waste, and the term mechanical-biological waste treatment is used. An overview of the different options is given in Figure 25. In short, clarity on the different composting and organic recycling options for compostable material is necessary in order to avoid misuse and creating false expectations (FP7 OPEN-BIO).

So far, compostable materials have mainly been considered from the viewpoint of industrial compostability, in particular for packaging. There is, for example, the EN 13432 standard on the compostability of (plastic) packaging, first published in 2000 (CEN, 2000). This harmonised standard provides the assumption of conformity with the essential requirements of the Packaging and Packaging Waste Directive (94/62/EC). Other international standards such as ASTM D.6400 (ASTM, 2012) and ISO 17088 (ISO, 2012) also focus on industrial compostability only for plastics, similar to the first certification and labelling systems that have appeared on the market (OK Compost from TÜV Austria Belgium and the Seedling logo from DIN CERTCO). Only relatively recently has home compostability been looked at more closely, with a French standard published in 2015 (AFNOR, 2015). Directive 2015/720 calls on the Commission to ask the European Committee for standardisation to develop a separate standard for home-compostable packaging. Finally, AD has hardly been considered until now, although both organic matter and energy, in the form of biogas (a mixture of CO_2 and methane), can be recovered. While AD is mentioned in EN 13432 as the digestate produced during the process can be matured into compost in a second aerobic step, the development of a standard on acceptance criteria for anaerobic digestion seems highly warranted (FP7 OPEN-BIO).

Rather than being a widely applicable, general solution for waste treatment, compostability should be considered for specific situations and applications that generate particular benefits. Firstly, specific materials can be perfectly compostable, but this does not mean that all products made from such materials can be considered compostable too. For example, for packaging in industrial composting the content should also be compostable. Secondly, it is of little help if a compostable material is put on a market where no system to collect and process it exists. More broadly, compostable products should fit within a local organic waste stream, going to a composting plant. Furthermore, compostable products which are mixed or attached to wet organic waste, such as food leftovers, can return nutrients to the biosphere. In addition, as these products are usually moist or soiled when disposed of, mechanical recycling would often require additional cleaning, increasing technical or economic hurdles. Some applications include coffee capsules, tea bags, stickers on fruit, bags for fruit and vegetables, yoghurt pots, napkins, takeaway food trays or pots, and pizza boxes. These products generate beneficial effects by increasing or facilitating collection of organic waste (e.g. through use of compostable bags), improving the composting process (e.g. by adding an extra carbon source and thereby decreasing the negative effects of too much nitrogen), and improving compost quality (e.g. by reducing contamination by otherwise non-compostable items such as fruit stickers) (Favoino, 2005 and World Economic Forum, Ellen MacArthur Foundation and McKinsey & Company, 2016 and VLACO, 2017). On the other hand, compostable plastics can generate issues when used for other specific applications, including loss of material value (e.g. for applications for which reuse or recycling is a cost-effective after-use pathway, such as bottles), biodegradation issues (e.g. products without third-party certification of compostability, or industrially compostable products in sub-optimal home composting), and littering (e.g. lack of awareness that industrially compostable products do not biodegrade in the environment).

Challenges and knowledge gaps

There is a lack of biological waste treatment capacity in Europe. While in some countries (e.g. the Netherlands, Germany and Belgium) separate organic waste collection combined with biological treatment is well established, in many others it is still in its infancy. As a consequence, large amounts of organic matter and nutrients are lost to recycling and recovery. Only 25 % of biowaste is collected and organically recycled throughout Europe, while the rest, roughly 100 million tonnes annually, is lost as a valuable resource (European Bioplastics, 2018).

Significant barriers to compostable plastics still exist at a legislative acceptance level. For example, in several countries compostable plastic items are not accepted in the organic waste stream. Not enough distinction is made between truly compostable plastics and false claims, and between applications where compostable material brings benefits and those where it does not.

Confusion and lack of proper understanding lead to false claims and limited uptake of compostable plastics. So far, a lot of effort has gone into technical improvements, including barrier properties, and into improving the economic and environmental aspects of production (H2020 BIOCOMPLACK, H2020 HYPERBIOCOAT, FP7 BIO4MAP and FP7 EUROPHA). The same effort does not seem to have gone into education, communication and supportive legislation. While authorities want to stimulate R&I in this field, many non-scientific barriers persist and remain a significant challenge to further spontaneous market development.

There is a lack of standards related to compostable plastics. While a European standard on industrial compostability of packaging was first published in 2000 (CEN, 2000), including both test procedures and specifications, a European standard on home compostability is still under development. In addition, the work on the compatibility of biodegradable and compostable packaging with anaerobic digestion plants still needs to be started, though proposals have been made (FP7 OPEN-BIO).

Policy recommendations and R&I priorities

Policy recommendations

Develop and implement a legal framework for communication about biodegradation under controlled conditions, i.e. home/industrial composting and anaerobic digestion. Such a framework should ensure a distinction is made between industrial compostability, home compostability and compatibility with anaerobic digestion technology. Any claims made should be based on the appropriate information available and third-party validated (i.e. certification).

Invest in infrastructure to expand biological waste collection and treatment capacity in order to harmonise and simplify collection systems, including clarity on disposal of compostable materials. Organic recycling of these resources would help retain their value in our economy (e.g. nutrients and minerals) and help increase the level of organic matter in soil, which would bring benefits for agro-technical reasons. The current capacity of industrial composting and anaerobic digestion needs to be increased to deal with larger volumes of organic waste. Compostable plastics and packaging can play a beneficial role by helping to collect a higher share of moist food and kitchen waste.

Develop an assessment methodology to understand for which applications compostable material should be used, based on an environmental, social and economic point of view. Such a methodology should take a life-cycle approach to avoid the shifting of burdens and provide clear decision criteria for evaluating different after-use options (e.g. mechanical, chemical and organic recycling) with regard to their environmental, social and economic footprint.

Set regulatory requirements related to the compostability of products based on their environmental, social and economic impacts. Measures should be taken based on the assessment of the impact of different applications. Depending on the assessment outcome, use of compostable material could be recommended or made mandatory, for example, for tea bags, coffee capsules, stickers for fruit, and organic waste collection bags. Measures could also be used to discourage or prohibit the use of compostable material for applications where it would not bring added value, and where other after-use pathways such as reuse or mechanical recycling would be more appropriate.

Provide information and business guidance on the different after-use pathways, and their complementarity. For example, mechanical/chemical recycling is preferred for clean and dry mono-materials such as beverage bottles, whereas composting could be the preferred option for packaging soiled with moisture and food residues as well as some multi-materials. General information could be provided at the EU level, while information related to the actual local conditions (e.g. to which facilities separately collected material is transferred to, how the material is treated and what happens to the resulting output) can be shared at a local or regional level. The target audience should include citizens and business alike.

Support the development of a European standard on compatibility with different anaerobic digestion technologies. More than 25 % of biological waste treatment takes place through anaerobic digestion and this share is only growing (De Baere & Mattheeuws, 2012). Currently, there are no specific European or international guidelines or standards for the acceptance of plastics or packaging by anaerobic digestion plants that take into account the specific constraints of different AD technologies.

9.2 Biodegradation in uncontrollable conditions

State of Play

A distinction needs to be made between biodegradability in composting environments and biodegradability in various other environments, as biodegradability can be different from one environmental habitat to another. The claim of a product being biodegradable can be misused as it does not really specify whether something is fully biodegradable within a given timeframe or only partly, and which environment it is intended for. Besides, biodegradability alone is not sufficient but should always be linked to environmental safety.

As is the case for composting, biodegradability in the environment cannot be considered as a widely applicable, general solution, but should instead be seen as a material choice option for specific situations and applications. Biodegradability could be wrongly perceived as a justification for allowing the leakage of packaging and other products which can be disposed of properly in a controlled waste system. In this case, there is clearly no reason to justify the negative environmental impact of littering or the loss of value by foregoing (organic) recycling. However, for a few products that are prone to end up in the environment, biodegradability options in situ or in a specific environment could make sense to mitigate the negative impact, assuming a range of other upstream measures are fully exploited (e.g. prevention). As biodegradability may vary depending on the specific environmental habitat, it is important to determine biodegradability in the correct environment. For example, biodegradable mulching film in agriculture should be biodegradable in soil, as is the case for trimming threads, and soluble sachets for dish washing powder should be biodegradable in freshwater (CEN, 2018). Disadvantages appear when biodegradable plastics are wrongly used for certain applications, often ignoring more profound long-term solutions. By using biodegradable alternatives for carefully selected products, the environmental damage due to the use of conventional plastics could be mitigated.

At this moment, a lot of research and development is being done to replace conventional plastics with biodegradable alternatives (H2020 BIOMULCH, H2020 FRESH and FP7 DEGRICOL). One study estimates that the period 2017-2022 will see continued growth in the global production capacities of biodegradable plastics (European Bioplastics, 2017a). Such growth in activity can partly be explained by the growing trend to brand packaging as environmentally friendly, and hitherto it has not been strongly coupled to any development of systemic solutions to collect and organically recycle the packaging (European Bioplastics, 2017a). While the awareness of biodegradable material options is growing, there is also scepticism about the extent of biodegradability as well as environmental safety (Lambert & Wagner, 2017 and Harrison & al., 2018).

Approaches using microorganisms for achieving biodegradation of otherwise non-biodegradable polymers are still at laboratory scale, and their potential remains to be seen. For example, Section 8.1 discussed how PET and PU/PURs are suitable for depolymerisation, a form of chemical recycling (Aguado, Martinez, Moral, Fermoso & Irusta, 2011). The same polymers can be used to feed special bacteria that can transform PET and PU/PURs into PHAs, which is a biodegradable polymer used in different applications (H2020 P4SB). This is an embryonic technology and it is currently limited to laboratory level. Research on the identification of naturally occurring plastic-degrading microorganisms and improved biotechnological processes for treating (conventional) plastic waste is happening (including mealworms consuming PS and marine bacteria metabolising PE), but no major breakthroughs have been achieved so far (FP7 BIOCLEAN and Austin et al., 2018).

The controlled use of slowly biodegradable plastics could be beneficial for certain applications with a relatively long lifespan, but there is a

high likelihood of leakage into the environment during wear and/or use. In contrast to compostable or environment-specific biodegradable plastics, which are intended to degrade relatively fast, slowly biodegradable plastics could be called 'non-persistent'. Typically, fast biodegradation is not really an option when the functional life has to be relatively long. However, for certain applications with such a lifespan, and a high likelihood of leakage into the environment during wear and/or use, environmental persistence is not desirable either. In these selected cases even (very) slow biodegradability would be preferable to the normal persistence. Potential applications include car tyres, shoe soles and fertiliser coating. Biodegradation should obviously take place in soil, in freshwater or in marine environments.

Alternative approaches that aim to render conventional plastics degradable, have so far turned out to be unreliable or even damaging. Several options have been proposed, such as oxo-degradable plastics, and bio-mediated degradable plastics, but results have not been promising so far (De Coninck & De Wilde, 2013). Moreover, existing evidence suggests that the former generate concerns about negative environmental impact by fragmenting into microplastics that do not biodegrade further. Therefore, as mentioned in the European Plastics Strategy, the Commission has started work with the intention of restricting the use of oxo-degradable plastics in the EU (European Commission, 2018j).

Challenges and knowledge gaps

There is a lack of testing methods and international standards on how to determine biodegradability in multiple specific environments. The development of criteria for accepting a particular material in specific environments, including requirements on the rate of biodegradation and on environmental safety, still needs to happen (FP7 OPEN-BIO). In this context, toxicity tests could also be further improved for several environments, including marine and soil environments, home composting and anaerobic digestion.

There is a lack of labelling and certification systems. Whereas schemes are in place for industrial compostability, they hardly exist for other environments such as home composting, or biodegradability in soil or freshwater. Only one certificate provider has recently become active on the market in Europe (TÜV Austria Belgium).

There is confusion and a lack of understanding about biodegradable plastics. Confusion and false communication are still around. As explained above, it is important to carefully select applications where the use of biodegradable plastics brings benefits. In this context, a distinction can be made between general consumers for whom information and education might be too broad, and users of specific applications, for whom information and education can be much more focused. For example, it is often easier to inform a farmer about the use and benefits of biodegradable mulching film in agriculture than a consumer about compostable packaging in general.

Policy recommendations and R&I priorities

Policy recommendations

Develop and implement a legal framework for communication about biodegradability, including a reference to the specific environmental habitat. For example, the claim that something is 'biodegradable' should not be allowed, whereas the claim 'biodegradable in soil' could be. Preferably this would happen within the context of a specific European or international standard (e.g. the CEN EN 17033:2018 standard on biodegradable mulch films for use in agriculture and horticulture). The framework should make sure that such claims are based on the appropriate information available and third-party validated (certification). Such a framework should be organised at a European level and ensure that communication is not only informative but also educational.

Develop an assessment methodology to understand for which applications biodegradable material should be used, based on an environmental, social and economic impact point of

view. Such a methodology should take a life-cycle approach to avoid the shifting of burdens and provide clear decision criteria for evaluating different after-use options (e.g. mechanical, chemical and organic recycling) with regard to their environmental, social and economic footprint.

Set regulatory requirements related to the biodegradability of products based on their environmental, social and economic impacts. Measures should be taken based on the assessment of the impact of different applications. Depending on the assessment outcome, use of biodegradable material could be recommended or made mandatory, for example, for mulching film and certain agricultural or horticultural accessories. Measures could also be used to discourage or prohibit the use of biodegradable material for applications where it would not bring added value, and where other after-use pathways such as reuse or mechanical recycling would be more appropriate.

Provide information and education on proper disposal, targeting the correct after-use pathways. Politics and legislation should play an active role in this education, in collaboration with industry. Support should be redirected from mainly technical guidance to support at the level of communication and education.

Support the development of European standards on biodegradability in various environments. Such standards should include biodegradation test methods, biodegradability specifications and test methods and specifications for environmental safety. For example, the European standard on biodegradable mulching film in agriculture could be expanded to also include other agricultural and horticultural accessories (CEN, 2018).

9.3 General facts and misunderstandings

State of Play

While biodegradable and compostable plastics have already been on the market for more than 25 years, a significant market breakthrough has not taken place yet. Several reasons can be identified for this slow uptake, as partly explained above. High prices and poor technical performance have played an important role, especially in the early years and still today to a certain extent (FP7 EUROPHA). In addition, insufficient supply, both in terms of the quantities produced and in the number of suppliers, have been obstacles to growth. Biodegradable plastics have also often been presented in a very general, almost unrealistic way, creating false expectations and damaging credibility.

More recently, non-technical obstacles have become increasingly important. These obstacles include (correct) information, education and legislation. Examples include wrong communication about correct environmental disposal routes (industrial versus home compostability), insufficient information on what biodegradability really entails, and prohibitions on collecting certain compostable products via the organic waste stream.

Information for citizens is limited, generic, and sometimes contradictory, misleading or false. For a good understanding it is important to note that a compostable plastic is more than just a biodegradable plastic, because besides ultimate and complete biodegradability it also entails timely disintegration and the absence of toxicity. As biodegradation depends on the specific environmental habitat, the environment should always be mentioned when making a claim about biodegradability. Because of the difference in properties, useful applications, and potential benefits and disadvantages, definitions must make a clear distinction between compostable plastics and environment-specific biodegradable plastics, as discussed in the above sections. Besides these nuances on environmental habitat, it is also important that standards on acceptance criteria for biodegradability should include requirements regarding environmental safety (chemical analyses and toxicity tests) (FP7 OPENBIO and Harrison & al., 2018).

Linked to the lack of information, there are misunderstandings due to a lack of education. In many cases, citizens have not been taught how to dispose of compostable plastics in the proper way, leading to cross-contamination of after-use pathways or littering. In addition, there are still several misunderstandings about compostable and biodegradable plastics:

- **It is a misunderstanding that biodegradable plastics offer a solution to the littering problem** (De Coninck & De Wilde, 2013). In contrast, a more common consensus is a fear that labelling items as biodegradable will only stimulate littering and steer consumers to incorrect disposal behaviour. In some cases, this has even led to legislation prohibiting any claims about biodegradability for packaging, while permitting claims for compostability as this is a managed waste disposal option (Belgisch staatsblad, 2008). Communication, education and legislation should be more specific and indicate clearly where biodegradable and compostable plastics could bring benefits and where they are less suitable. This change from a general to specific approach is a positive evolution, which can also be considered as a maturation in the concept of compostable and biodegradable plastics as one of several options of how to create safe and value-preserving after-use pathways for plastics.

- **It is a misunderstanding that bio-based materials are inherently biodegradable.** This is obviously not the case. Although there are often links, no structural relationship exists between the properties of being bio-based and biodegradable (see Chapter 4). 57 % of all biodegradable and/or bio-based plastics are bio-based and non-biodegradable. Of the remaining 43 % which are biodegradable, 76 % are bio-based and 24 % are fossil-based (European Bioplastics, 2017a).

- **It is a misunderstanding that biodegradable plastics, by definition, contribute to the problem of microplastics in the environment** (De Wilde, 2018). This is partly caused by an insufficient understanding of biodegradation, and partly by confusing and incorrect communication from industry. In particular, doubt is created by the 90 % pass level for biodegradation. In fact, 100 % should not be expected as this threshold is based on the carbon to CO_2 conversion, while the carbon converted to biomass carbon cannot be measured (FP7 OPENBIO). Correct disposal, standards, specifications and communication about biodegradation should be clear and sufficiently stringent to illustrate and make sure that biodegradable plastics do not contribute to microplastics in the environment.

In general, compostable and biodegradable plastics relate to mechanical or chemical recycling in a similar way to many other conventional plastics. The impact of compostable and biodegradable plastics on current collection, sorting and recycling systems can be positive or negative, as with conventional plastics. When collected and processed in a material stream they should have been excluded from, compostable and biodegradable plastics easily become contaminants. This holds for most plastics that should have been sorted out, regardless of their ability to biodegrade. Mechanical and chemical recycling of biodegradable and compostable plastics is also similar to the recycling of conventional plastics. When presented as pure streams of mono-materials most compostable and biodegradable plastics can be mechanically recycled reasonably well, and some even chemically (e.g. PLA). This property allows different after-use pathways, depending on the application and overall benefits. For example, if PLA is used for carpet tiles, mechanical or chemical recycling could be the preferred option, whereas if used for food packaging with a high likelihood of leftover food contamination, organic recycling may be preferable.

Legislation for biodegradable plastics seems to apply double standards compared to that for conventional plastics. While it is justified to minimise the risk of regrettable substitution, biodegradable plastics often need to satisfy a range of requirements before being acceptable as an alternative, including demands never made of conventional plastics. Biodegradable mulching film, for example, comes under scrutiny with questions about the fate of minor amounts which may end up in a marine environment. On the other hand, at least 20% of conventional plastic mulching film leaches into the environment, but this raises few questions (H2020 BIOMULCH).

Roughly 20 large families of biodegradable and compostable plastics currently exist, each with benefits and drawbacks, lending themselves to specific applications. Just as with conventional plastics, complementarity between different plastics can be useful. Several applications combine different compostable or biodegradable materials to obtain better mechanical and functional characteristics. A relevant benefit of this complementarity is the use of multiple compostable materials to create a multilayer without any effect on the compostability. This is in contrast to mechanical recycling, which requires products to be mono-material as far as possible in order to achieve maximum recyclability. Using multiple layers is important for several types of packaging. For instance, laminating flexible films is important for technical performance, e.g. barrier function for light, oxygen and moisture (H2020 HYPERBIOCOAT and H2020 BIOCOMPLACK). In addition, compostable plastics can be used for coating paper in order to obtain a structure which is entirely compostable.

Challenges and knowledge gaps

Many authorities support R&I in biodegradable/compostable plastics but hold back on their application. While research, (technical) development and investment in biodegradable/compostable plastics is supported, implementation of the outcomes is not reinforced by supportive legislation, or may even be hindered (H2020 HYPERBIOCOAT, H2020 BIOCOMPLACK and FP7 OPEN-BIO).

As opposed to standards for test procedures, standards for criteria and specifications are still lacking for some environments. These should not only include requirements with regard to biodegradation but also with regard to environmental safety. In addition, standards should continuously be improved and updated when new insights are obtained.

Vertical organisation of standards leads to additional work and conflicts. Currently, standards are organised in a vertical way, which means standards become available per product or per material and this can sometimes lead to conflicting situations. Moreover, it means work needs to be repeated, making standardisation more cumbersome, with for example one standard on the industrial compostability of packaging and one on plastics, although the two standards are basically the same (CEN, 2000 and CEN, 2006). Although other standards have the same rationale they differ in some detailed requirements (CEN, 2000 and ASTM, 2012).

Policy recommendations and R&I priorities

Policy recommendations

Harmonise different policymaker measures, including legislation, to provide clear direction for R&I and implementation of compostable or biodegradable materials. Authorities often have a dual approach, reflected for example through financial support for R&I in compostable plastics, but lacking a coherent regulatory framework for its implementation.

Harmonise the organisation of different standards, exploring a horizontal organisation, i.e. one standard for all products in a specific environment. Currently, standards are written for material or product categories, but for environmental purposes they should be organised from the viewpoint of each environment. For example, the CEN standard on biodegradable mulching film in agriculture could be expanded and/or adapted to also include other agricultural and horticultural products (CEN, 2018).

R&I Priorities

Provide funding for research and financial incentives for innovation in compostable and biodegradable materials for specific environments. Such R&I should be tailored to specific products and applications based on a holistic assessment of environmental, social and economic impacts.

Provide funding for research on the impact and feasibility of different after-use options for specific products and applications. Research should inform design and production, policymaking and (infrastructure) investments.

Provide funding for research on process approval parameters for standards for organic recycling and biodegradation in specific environments. Such research should subsequently inform the development of standards.

APPENDICES

APPENDIX: SUMMARY OF FINDINGS PER CHAPTER

References for statements in the summaries below can be found in the respective chapters.

Part I: The unintended impacts of plastics on society and the environment

1. Plastic pollution

Since the beginning of plastics' mass production in the 1950s, about 4 900 million tonnes of this material have been disposed of in landfills or in the environment. The resulting plastic pollution is omnipresent and persistent on a global scale, with even the remotest locations affected. This situation has triggered public concerns and actions in the European Union and elsewhere, for example regarding single-use plastics. Current knowledge of the sources of plastic pollution is largely based on estimates, with rivers being the main transport pathway carrying large amounts of plastic debris to the oceans.

Since the causes of plastic pollution form a highly complex problem involving much scientific uncertainty, it is challenging to identify simple cause-and-effect patterns to inform action. Hence, while additional research about the sources, fate and impact of plastics on society and the environment is needed, the lack of holistic understanding should not prevent action to develop and implement effective solutions. In particular, policymaking should enable, and be supported by, R&I that combines an understanding of the key processes of the problem with the development of solutions.

Plastic pollution is a clear shortcoming of the current take-make-dispose plastics economy. While clean-up activities could be a short-term necessity, the long-term solutions address the problem more fundamentally upstream in the value chain. Accordingly, innovations should aim to tackle the problem at the root, guided by the most recent scientific evidence. Priorities to address this global issue will differ for developed and developing economies, ranging from innovating business models to installing waste management systems, but ultimately the solution will need to be systemic.

2. Substances of concern to human and environmental health

In general, plastics are complex chemical mixtures and contain a range of chemicals, both intentionally and non-intentionally added. The intentionally added chemicals are used for different functions and enable different properties to the benefit of users. Some non-intentionally added substances present in plastics are unknown, which hampers chemical risk assessment.

The impact of chemicals on human and environmental health are evaluated using risk assessments, regulated in national and EU legislation, such as REACH. Chemical risk assessment requires information on both exposure levels and the toxicity properties of a substance. Toxicity testing requirements are mostly tiered by production volume or human exposure levels. Current risk assessment approaches mostly do not address mixture toxicity, aggregate exposures, the presence of unknown substances and endocrine disruption. While supporting the transition towards a circular economy for plastics, recycling could lead to the presence of chemicals of concern in ecosystems or in new products. Regulation could be strengthened by harmonising existing legislations (e.g. across product categories), by extending risks assessment to the entire life cycle of plastic products (e.g. dealing with non-intentionally added substances in finished articles), and by closing certain gaps in legislation (e.g. some substances have no legal requirement for assessment of their chemical hazard or risk).

R&I plays an important role in improving both hazards and risks assessments, and safer alternatives development. For example, while *in silico* and *in vitro* tools seem promising approaches for hazard assessment, they need to be developed further in order to reduce scientific uncertainty. Design innovation deserves particular attention, as the positive impact of substituting hazardous substances in new (plastic) products is likely to be larger than removing legacy elements in recycled materials. Aiming to avoid regrettable substitution, such design innovation should focus on function in the broad sense. This approach fuels innovation in new business models, products and materials that address the same need, but avoid hazardous substances altogether.

Part II: Novel sources, designs and business models for plastics in a circular economy

3. New materials

Today's plastics industry is defined by a fossil-based feedstock and energy paradigm. The large-scale capital intensity and decades-long optimisation of the petrochemical industry have become barriers to introducing new materials that do not fit into this existing infrastructure. Thus, despite many efforts at European, national and local level, scale-up and commercialisation of bio-based feedstock or completely novel (plastic) materials remains rather limited.

As a consequence of this inertia, it is not realistic to assume the plastics system will reinvent itself in terms of sourcing and approaches for the production of novel plastics. As evidenced over the past 50 years of research and commercial development, most efforts on novel plastics have singularly been aligned to the capabilities and interests of the initiators. In this way, the linear plastics system has been optimised, along with its benefits and shortcomings, instead of moving the entire value chain towards better economic, environmental and social outcomes in the long term.

Policymakers are well-positioned to break this stalemate by creating a mechanism for shared responsibility and accountability across the value chain through, for example, product requirements, extended producer responsibility schemes and taxation. Shifting towards a new material paradigm would need cross-sectoral and cross-value-chain collaboration to drive innovation that considers the entire system, rather than narrow specifications. In addition, policymakers could ensure coordination and consistency of efforts across Europe, moving towards a common direction. Finally, innovation towards this new paradigm needs to be strengthened through both funding and non-financial support. On the one hand, regulatory measures should incentivise private expenditures for the short-term addressing of existing issues. On the other hand, they should support the financing of long-term innovation and investments towards shifting away from the fossil-based paradigm, by leveraging the existing chemical infrastructure and by supporting the development of new dynamic, small-scale, decentralised business and biorefinery models.

4. Biological feedstock

Over the past few decades, many resources have been invested in developing pathways to produce plastics from biological feedstock. Nonetheless, compared to plastics based on fossil feedstock, bio-based plastics have not yet scaled up. This situation is mainly attributed to the low oil price and scale advantage of the existing fossil-based industry, to low maturity in processing and recovery technologies and, for particular applications, to performance and functional disadvantages. In addition, the initial success of so-called 1st generation biological feedstock, such as corn and sugarcane, coupled with some economic, social and environmental concerns related to food and feed competition, has triggered further research towards more early-stage 2nd and 3rd generation feedstock, including forestry residues and agricultural waste.

Biological feedstock can be seen as a source of the necessary platform chemicals and polymers to be turned into plastics. The type of biological feedstock influences the production yield and efficiency, but not the performance of a bio-based polymer. However, the composition of the feedstock influences the ease with which a specific type of biomass can be converted into different chemicals or polymers. The variety of biological feedstocks available across the EU offers opportunities to develop such a chemicals platform but requires an EU-wide approach to connect supply and demand. Most estimates of the current and future biomass potential in Europe take a bioenergy and biofuel perspective. The available amount and geographical spread of biomass for producing chemicals and plastics are less clear though, as is the expected evolution. Further research is needed to understand the potential conflict arising from demand for biomass for energy, feed and food, and chemicals and materials, and from overall environmental and social impact. In addition, in a circular economy, the role of bio-based plastics for decoupling from fossil feedstock has to be clarified, ensuring complementarity with the increasing use of recycled content, other alternative feedstocks, such as CO_2, and dematerialisation.

In the past, European R&I projects in this domain have often focused on fundamental research, which has led to significant development of bio-based polymers and chemicals. Consequently, and in line with the updated EU Bioeconomy Strategy, future support should shift attention to projects that aim to develop this R&I further by looking into scale-up, commercialisation and market introduction of the bio-based polymers and chemicals for which there is a positive social, environmental and economic impact compared to alternatives.

5. Business models, product and service design

The introduction of a circular economy framework impacts the approach to business model development and product design. Since plastic items often move fast through a value chain, and involve multiple stakeholders, developing business models in line with circular economy principles requires a high level of structural cooperation, supported by policy. So far, designing products and business models for a circular economy has not been widespread in plastic products, especially in packaging.

Business model and product design innovations need to be rooted in a strategic vision initiated from a market need or clear user-centred insight. The innovation process has to be feedback-rich and able to adjust itself to handle the added complexity of working in a context involving multiple stakeholders. Managing the uncertainty in such an innovation process, including the complexity of the circular economy and ‘unknown unknowns’, requires a new approach to funding, planning and managing innovation projects. Starting points are, from an academic perspective, the foundations of transition management, and on a pragmatic level, the fundamentals of design thinking. A strong and stable policy-supported vision is needed to install trust throughout the value chains and across sectors.

While there is evidence that product design has started to take a more systemic approach, current R&I typically focuses on specific aspects of the entire system. Design that works for the entire system, which is crucial for the transition towards a circular economy, is still not considered widely. This is hard for product design since it requires taking into account much more complexity of the system, while making the product itself less complex, reflected for example through ease of disassembly. Product designers need support to collaborate on strategic innovation with stakeholders from the whole value chain, in particular end users and recyclers.

Information transparency is a crucial ingredient in designing circular business models and products since multiple stakeholders are involved in handling the products and materials. Several mature approaches and technologies exist to trace and generate data about products, but none have been tested at scale in the context of plastics value chains. Policymakers should, together with industry, address the key challenge of how to create a system of shared information, while making sure intellectual property is protected and competitiveness is handled fairly.

Several linked trends towards more interconnectedness and information sharing – even at business level – enable circular business models and design. In addition, they create opportunities to scale ideas that have previously been small niche ideas towards the mainstream. Examples of successful circular economy models have shown responses to these trends and opportunities, such as the safe-by-design concept. In parallel, strong trends such as increasing convenience and 'on-the-go' consumption drive the status quo in plastics and packaging. As the innovation process for circular business models has to incorporate additional complexities, policy can support the transition by providing financial incentives or setting a favourable regulatory framework.

Part III: Circular after-use pathways for plastics

6. Collection and sorting

Collecting, sorting and recycling plastics bring economic and environmental benefits, but the current system faces capacity and modernisation challenges. Proper collection of used plastics lays the foundation of an effective after-use system and determines the maximum amount of plastics that can be reprocessed further downstream. Across Europe, there is a large variety of collection and sorting systems in use, with differences in what materials are collected and where, and whether or not manual pre-sorting is done by the user. While adaptation to certain local conditions is needed, such fragmentation negatively affects the efficiency and cost-effectiveness. Hence, policymakers should support the consolidation of best practices into a more harmonised collection system. While manual pre-sorting at home and centralised separation both have their benefits and disadvantages, sorting results could overall be improved through developing and implementing new (digital) technologies, such as automated vehicles, smart devices and robotics.

The plastics landscape is, however, complex and continuously evolving due to both established and emerging socioeconomic and innovation trends, including lightweighting, new materials and manufacturing techniques, new business models and societal trends, and global trade. Policymakers can address this complexity by connecting upstream design and production phases with after-use collection and sorting, for example, through EPR schemes with modulated fees. New policy measures supporting cross-value-chain collaboration and industrial symbiosis would further improve the collection and sorting of plastics to be recycled for use in the same or different sectors.

7. Mechanical Recycling

There is untapped potential in the current recycling system, and with technical improvements the ability to process used plastics can even increase and generate further benefits. However, high-quality mechanical recycling is impaired by the increasing complexity of the material and products landscape. For example, recycling challenges are posed by composites, thermosets, multilayers, inks, labels and adhesives. Furthermore, multiple grades and the presence of additives mean that below-virgin quality is an inherent property of mechanically recycled polymers. This lower quality makes it difficult for mechanically recycled plastics to compete with virgin feedstock or to fulfil regulatory requirements. R&I can help to overcome this barrier, for example, by designing materials and products better suited for recycling, and by developing and piloting high-quality recycling and decontamination technologies.

In addition, the price difference between virgin and recycled plastics is a crucial challenge. One reason for this situation is the underdeveloped European market for recycled plastics – a result of the past reliance on exports of after-use plastics. This could be partly addressed by growing the market for recycled plastics with active efforts to identify new outputs and applications based on better matching of quality and demand. However, even if the market develops and scale increases, mechanical recycling faces a cost challenge as long as externalities are not accounted for. Fiscal measures addressing the costs of negative externalities, such as greenhouse gas emissions, could help to overcome the price challenge. Policymakers can further support a well-functioning secondary materials market through facilitating matchmaking (e.g. EU-wide standard for recycled grade qualities), harmonising existing legislation (e.g. on legacy additives), ensuring sufficient sorting and recycling capacity, and developing a favourable regulatory framework (e.g. mandatory level of recycled content for certain applications while safeguarding health). R&I should focus on understanding the mechanisms, routes and systemic reasons for the successful use of recycled plastics in certain applications, and its replication potential.

8. Chemical recycling

Solvent-based purification and depolymerisation are two reprocessing technologies that use chemical agents or processes that directly affect either the formulation of the plastic or the polymer itself. They can complement mechanical recycling because they produce (near) virgin-grade polymers from after-use plastics. Since they can remove additives and contaminants and generate 'as-new' polymers, they could play a role in creating an effective after-use economy for plastics. Most efforts are still at research or pilot stage, however, and more insight is needed into how competitive they will be at industrial scale, what the environmental impact would be, and how to best integrate them into the existing collection and recycling infrastructure.

Pyrolysis and gasification transform plastics and most of its additives and contaminants into basic chemicals, which can be refined into new materials using the existing petrochemical industry infrastructure. Their main advantage is that they can handle mixed and contaminated input, which in the current plastics system is produced in high volumes (e.g. as rejected residue in plastics recycling facilities). However, there is no guarantee that the output chemicals will be converted to new materials, given the environmental considerations such as energy requirements. In fact, the output from pyrolysis can also be used as a fuel, which is mostly how it is used today. In this case, pyrolysis and gasification, if scaled-up, would only propagate a linear fossil-based plastics economy, including several of the challenges faced today. This prompts a systemic assessment of the potential role of these technologies in the after-use system, and providing innovation support according to its findings.

In general, in a plastics economy that generates a large amount of materials that are difficult to treat with mechanical recycling, chemical recycling technologies can be complementary for two main reasons. Firstly, they are able to generate virgin-quality recycled materials. Secondly, they can process material streams which are mixed, contaminated or of unfeasibly low volume (e.g. novel materials). However, many questions remain about how to make chemical recycling work at scale, from a market, infrastructure and legislative perspective, and what the overall economic, environmental and social impacts are. To gain clarity, policymakers should stimulate further innovation and revise the regulatory landscape, including the legal status of different output materials, based on an impact analysis compared to alternatives. As with all after-use options, the performance of chemical recycling and the extent of value creation are subject to the design and material choice of plastic items put on the market – an insight that reinforces the importance of the upstream design of and innovation in new business models, products and materials.

9. Organic recycling and biodegradation

Composting and other organic recycling, such as anaerobic digestion, fit into a circular economy through the idea of closing the biological loops. Compostable plastics can support the organic recycling of biowaste, if the material has the right biodegradation properties and adequate infrastructure is present (e.g. collection of food leftovers). Under the assumption there is a clear link to environmental safety, biodegradable plastics could play a role in particular applications. Hence, rather than being widely applicable, general solutions for waste treatment, compostability and biodegradability should be considered for specific situations and applications, generating particular benefits.

There is still confusion and lack of understanding about compostable and biodegradable plastics, and their possible role in a circular economy. Policymakers could create clarity for citizens and business alike by enforcing correct communication, validated by third parties, and providing guidance on applications where the use of compostable or biodegradable plastics would be appropriate. Furthermore, understanding can be improved by communication about and further development of test methods and international standards on how to determine compostability and biodegradability in specific environments, and across different environments. The organisation of such standards should be harmonised, and could explore using a horizontal method (i.e. one standard for all products in a specific environment). Adequate collection and sorting infrastructure is another requirement to avoid cross-contamination with other recycling routes. In addition, different policy measures, including legislation, should be harmonised to provide a clear direction for R&I in, and implementation of, compostable or biodegradable materials.

APPENDIX: OVERVIEW POLICY RECOMMENDATIONS

The following recommendations have been proposed by the experts based on the state of play and challenges and knowledge gaps, gathered through reviewed projects, available public knowledge and their own expertise. The recommendations have subsequently been synthesised and edited following feedback from a wider stakeholder group.

General cross-value-chain insights

- **Collaborate towards a common vision across the plastics value chains to trigger actions at regional, national, European and global level.** Given their long-term perspective, policymakers are uniquely positioned to convene, frame and drive the discussion on such fundamental systemic change. Collaborative platforms should develop a thorough understanding of the current plastics system, and create a common vision of a circular one. In addition, to enable this collaboration and subsequent actions, policymakers should demand tangible outcomes. To expand our knowledge on this global challenge in a coherent way, measures are required at national and international level. Policymakers should ensure well-defined, transparent and reliable data on plastics' impacts and flows is gathered and shared systematically. For areas in which other stakeholders are better positioned to develop such mechanisms, policymakers could facilitate action.

- **Develop, harmonise and enforce regulatory and legal frameworks guided by systems thinking.** Key areas in scope include business models and product design, chemical safety and risk assessments, use and measurement of recycled content, compostability and biodegradability, and information sharing and (digital) technologies in the field of plastics. In these domains in particular, R&I would benefit from enabling conditions set by policymakers. Reviewing existing and setting up new regulation through a systemic lens could strengthen innovation towards a circular economy. Potential levers include standardisation of terminology and assessment methodologies, product requirements, and EU-wide harmonisation of legal structures and of different pieces of legislation in order to eliminate inconsistencies and close gaps in coverage. In addition, policymakers should further develop and implement product stewardship systems, such as extended producer responsibility schemes, to steer business model and product design towards reuse and high-quality recycling in a cost-effective way. As insights from R&I should strengthen policy decisions, the development of such enabling regulatory and legal frameworks needs to be an iterative process.

- **Set up, connect and fund mechanisms to coordinate the transition strategically and to invest in upstream and downstream capacity across Europe.** Strategic coordination is needed to keep track of ongoing activities and the interventions that need to follow to achieve systems-level change over time. A range of investment types, from project financing, over venture capital to private equity and institutional investments, are necessary to fund both infrastructure built-up across the value chain and to support R&I capabilities. Policymakers should pay particular attention to (co-)financing high-risk systemic innovation with a longer-term perspective, as often reflected in unconventional circular business models. To ensure strategic coordination and consistent investments, additional clarity on the direction of travel for the plastics system in Europe is needed. Policymakers should connect existing or set up new mechanisms to ensure public and private funding is spent in a strategic way, and ongoing and planned actions, such as new legislation or investments in recycling capacity, are mutually reinforcing. This approach should anticipate and eradicate the lock-in effect of infrastructure fit for the linear economy. In addition to guiding the flow of capital, policies need to influence shareholders to support behaviour change.

- **Provide funding for research and financial incentives for systemic innovation across the plastics value chain.** As research in these areas mostly deals with developing knowledge on plastics design, production, use and after-use handling, and on its impacts on society, grants will likely be the preferred instrument. Innovation incentives can, for example, take the form of public procurement, fiscal measures, grant funding and equity investments. It is important to note that the way funding calls are developed, and (proposed) projects evaluated and managed tend to determine how the projects will be carried out and what the potential outcome space will be. Hence, a systems thinking perspective needs to be taken when developing and managing projects towards systemic innovation, potentially enabling a more iterative approach to target-setting.

- **Educate and support citizens, companies and investors on the transition towards a circular economy for plastics.** Policymakers should ensure citizens and business alike receive clear evidence-based information about the benefits and shortcomings of plastics. Knowledge exchange can happen in different ways, including awareness raising campaigns and formal education. Based on behavioural insights, such knowledge should be shared to nudge people and trigger change in their actions. The uptake of new innovations can be fostered through (technical) support specifically targeting business, including investors.

Part I:
The unintended impacts of plastics on society and the environment

1. Plastic pollution

- **Harmonise definitions, frameworks for systematic data gathering, and analyses of plastic flows and pollution at European and global level.** It is critical to have a systematic and replicable collection protocol, and a commonly accepted terminology for analysing the data. A regulatory framework of standardised procedures for collecting, filing and analysing data on marine debris provide consistency and comparability.

- **Develop open collaboration platforms to enable more comprehensive analyses and frequent benchmarking on plastic flows and impacts, to provide information on and for investments, and to create political and public will.** Such platforms should enable inclusion beyond academia and facilitate innovation of new and more effective research and assessment methods. They are also crucial to identify key knowledge gaps, and should help coordinate frequent benchmarking of how plastic pollution contributes to global societal change, including ocean health and ecosystem degradation.

- **Develop risk assessment and policy frameworks based on a systems thinking approach.** The systemic and complex nature of plastic pollution needs to be taken into account when assessing the scale of the problem, as well as identifying and implementing solutions. Underpinned by the principles of a circular economy, take into account environmental, economic and societal costs and benefits of policy interventions and compare these to the costs of inaction.

2. Substances of concern to human and environmental health

- **Enforce, harmonise and adapt existing EU chemical regulations, including REACH, the Toy Safety Directive and the regulation on food-contact materials.** These actions should be in line with the ongoing ECHA work on information transparency, and include regulatory requirements for ink, labels and adhesives and other chemicals related to plastic products based on overall migration from finished articles. This can be achieved by enhanced enforcement of product testing by authorities or government-supported third parties, such as independent testing labs. Additionally, synergies between chemical policies should be improved, so product designers become aware of SVHCs and other hazardous chemicals that can be present in recycled materials if these are used as raw materials. For this purpose, it can be useful to develop a positive list, i.e. containing all chemicals authorised for use in plastics, and a negative list, i.e. listing all substances which are not permitted (see, for example, a positive list for plastic FCMs). These lists would allow for a qualitative safety assessment and assist with ensuring performance properties.

- **Set additional regulatory requirements for additives and other chemicals in plastic products based on overall migrate from finished articles at European and global level.** This measure should ensure that the party placing a finished product on the EU market is liable for the correctness and completeness of chemical content information. Such requirements include assessment of chemicals prone to migrate from finished plastics, testing for known and potential endocrine disrupting chemicals, setting ecotoxicological criteria for compostable or soil/marine/freshwater biodegradable materials, and creating more information transparency on additives and other chemicals used in plastics. In addition, impact assessment methods (such as LCA) should be expanded to account for chemical migration and toxicity during the entire life cycle. Particularly hazardous substances should be phased out for all product categories, driving substitution by safer alternatives. Measures should be pursued at European and global level to ensure a level playing field.

- **Provide business support and guidance to identify and reduce chemical hazards.** Such support includes information about known hazards and how to reduce them, guidance on how to assess intentionally and non-intentionally added substances to meet legal requirements for food-contact items, and guidance on the safety assessment of products containing recycled material.

Part II: Novel sources, designs and business models for plastics in a circular economy

3. New materials

- **Develop and implement regulatory incentives such as extended producer responsibility systems and shared responsibilities across the value chain to steer (plastic) product design towards reuse and cost-effective recycling.** This could include a shift towards reusable packaging, use of single materials or multi-material products which can be easily disassembled or (organically) recycled. The minimum general requirements on EPR as defined in the revised Waste Framework Directive (Article 8a) already go in this direction. In addition, develop a framework to ensure a joint value-chain responsibility regarding the environmental impact of materials used and to share R&I risk between all participating actors.

- **Provide and enable funding and financial incentives for infrastructure and (long-term)**

R&I that maximises plastics value retention. Large investments are needed for infrastructure to enable cost-effective reverse logistics, collection, sorting and recycling of materials, as well as to develop systemically useful innovations beyond early-stage R&I. Policymakers can provide direct funding as well as set up and facilitate investment mechanisms that pool public and private investments towards a circular economy for plastics. In addition, set up a plastics oversight board for strategic planning and long-term investments, and support businesses with guidance and financial incentives to incorporate into their R&I more systems thinking and business models based on circular economy principles.

- **Develop a platform for creating information transparency and for facilitating sharing and trading of R&I, taking into account the sensitivity of certain information.** On the one hand, such a platform could help implement a much-needed product information system using digital technologies, so that transparency can be achieved without compromising proprietary information. On the other hand, it would facilitate science and technology exchange, accelerate the development of systemic solutions and enable shared risk-taking.

- **Set up a coordination board for strategic long-term investments, combining technical, commercial and behavioural insights.** Based on latest R&I insights, such a board could set the strategic direction for investments, and work with matching private funds to accelerate the transition to a circular economy for plastics. The board should consist of policymakers, topic experts and investors.

4. Biological feedstock

- **Provide regulatory, legal and financial incentives to support (long-term) R&I in and scale-up of innovative renewable materials and chemicals towards a self-sustaining critical mass, guided by systems thinking and based on a holistic impact assessment across the life cycle.** The use of agricultural and industrial by-products and residual material streams, instead of virgin feedstock, should be incentivised at European and Member State level by providing regulatory and economic incentives, including mandatory quotas, tax incentives and feed-in tariffs or premiums. Green public procurement, for example through the EU public procurement directives, is another measure to boost the growth of this market. R&I support should mainly focus on projects that aim to achieve TRL 5 or higher to improve commercialisation and market introduction, and include supporting pilots and test markets. Clear regulatory and legal frameworks should facilitate the development of a decentralised multi-feedstock chemicals industry across Europe. Furthermore, as the valorisation of local bio-based feedstock can have a significant impact on regional economics, such business development needs to be supported through different financial instruments and regulatory measures. Legal frameworks for industrial by-products and waste should be simplified and harmonised, for example by redefining by-product and waste to ensure their utilisation as feedstock. Measures should be guided by a holistic assessment to understand the (long-term) impact.

- **Provide information about bio-based materials for citizens and business by developing standards, labels and a holistic impact assessment framework.** Such information should include data on the availability of biomass at regional, national and EU level, an understanding of biomass flows, consumption habits and environmental aspects of the entire production chain. Standards and labels can demonstrate technical specifications, the bio-based content, and measures for after-use handling. Such a framework should be used to compare plastics made from different types of fossil and renewable feedstock, including criteria for quantitative and qualitative impact assessment across the life cycle. It can inform investors on benefits and risks associated with the value chains.

- **Set up a strategic coordination mechanism to develop EU-wide planning for production and after-use handling infrastructure and to track existing and expected inventories to drive scale-up of renewable plastics and chemicals.** An EU-wide strategy for scaling biorefineries should stimulate collaboration or consolidation to create cost-efficient chemicals and plastics producing units. In addition, this should provide direction for investments in public infrastructure to enable collection, sorting and (organic) recycling of plastics after their use, regardless of their feedstock. In order to understand the potential and feasibility of developing bio-based platform chemicals and plastics at scale, the current and expected inventories need to be known. This coordinating mechanism should also support collaboration mechanisms such as industrial symbiosis that valorises production side streams.

5. Business models, product and service design

- **Facilitate gathering and sharing of reliable information and data to foster open innovation by knowledge exchange between innovators, industry and the public to ensure activation such as circular design training or circular public procurement.** By making abstract emerging business model patterns more widely available, with different use cases to support them, they can be copied and applied more easily by different organisations and sectors, e.g. in product design and procurement departments. Knowledge exchange between industry stakeholders should support data-driven open innovation, including a structured framework for data transparency to protect IP, competitiveness and citizens' privacy in line with the General Data Protection Regulation (GDPR). This requires developing guidelines and rules for third parties who gather the data, and providing oversight at national and EU level to encourage transparency and information exchange to ensure and maximise public interest.

- **Set up, connect and participate as an active stakeholder or shareholder in investment instruments to enable investors and lenders to provide funds for circular economy business models.** This involves creating incentives to fund business with unconventional balance sheets or models, e.g. through discounted credits, as well as mobilising research into how to develop KPIs and assessment models relevant for circular business models. A dedicated start-up accelerator at EU level, in line with a holistic circular economy system should also be considered. Governments should take a more active role in R&I projects at regional, national and European level. This could be both in the research and impact on policy innovation, as well as in launching relevant (from a bigger societal point of view) innovation challenges with a clear vision and making the project outcomes offer guidance for policy innovation, rather than defining the constraints too much beforehand. This active role could also be translated into taking more risks in supporting projects for the circular economy through, for example, investing in equity instead of grants.

- **Develop regulatory measures and incentives such as EPR systems, ecodesign and minimum product requirements to steer product design towards elimination, use of renewable or recycled feedstock, reuse and cost-effective recycling (Packaging and Packaging Waste, Ecodesign, and Waste Framework Directive).** The intended product design would include the use of mono-material or cost-effective separation of composites/multi-materials, and business models based on reuse and repair. Ecodesign should go beyond energy and resource efficiency by including other aspects of the life cycle, including chemical safety and social value. Requirements should include minimum recycled content for different product types to strengthen the recycled materials market, while avoiding negative impact on human and environmental health or skewed incentives.

- **Incorporate a holistic, circular approach and thorough testing and prototyping of business models as requirements in R&I projects, allowing enough freedom for shifting scope, focus and content (Horizon Europe).** A broader approach should incorporate the impact on human and environmental health of the entire lifecycle of the (plastic) products. For many R&I projects, the focus lies mainly on technical viability, whereas new business models require copious testing, prototyping and gathering of feedback. Most projects stick to the initially agreed scope for good reasons, especially in later stages once the hypothesis or concept has been proven. However, in early stages, this can stifle innovation that could occur when confronted with new insights through the research done (i.e. unknown unknowns). Giving more flexibility in shifting focus and acting upon new insights and knowledge could help in speeding up innovation and the relevance of the projects, and in the end making these projects more outcomes-oriented and thus fully aligning the project-outcome with its intention.

- **Develop product policies, standards and a holistic assessment methodology to assess and support the design of circular products, services and business models.** Product policies and standards should simplify the products landscape, balancing economic, environmental and social impacts by taking an outcomes-oriented approach. A universal evaluation methodology should bridge LCA shortcomings by including more systemic elements, providing guidance and orientation on how to design and what objectives to achieve (e.g. leveraging ecodesign, standardisation and financial incentives).

- **Incorporate systems thinking, circular economy and environmental impacts into the education curriculum at all levels to provide a solid knowledge base for future generations of designers and innovators.** Such a cross-cutting theme can complement the existing topical verticals in most curricula, while enabling the education system to better prepare students for the world's increasing complexity and ambiguity.

Part III: Circular after-use pathways for plastics

6. Collection and sorting

- **Enforce waste legislation and develop a regulatory framework to harmonise collection systems, allowing a certain degree of local adaptation to socioeconomic conditions.** Full implementation and enforcement of the EU waste legislation should guarantee proper collection and sorting of used materials across the EU. A suitable regulatory framework could encourage and facilitate convergence of best practices, allowing for a reasonable level of local differentiation. It could do so by introducing minimum standards on quality, hygiene and separation of items per sector. The European Commission will issue guidance on the separate collection of plastics, including best practices (European Commission, 2018j).

- **Develop regulatory measures, such as a stewardship framework and EPR with modulated fees, integrating new digital technologies, to cover costs of waste collection and processing, to incentivise product design towards circular pathways and to fund innovation in this field.** The connection between fees paid by a producer in a collective scheme and the contribution towards a circular economy should be strengthened. For example, this can be supported by a positive feedback mechanism to incentivise product design to support reuse or improve sorting and recycling, as outlined in the revised Waste Framework Directive. A collective scheme could also support crucial R&I. The current waste hierarchy should be reinforced with indicators and targets for reuse, and a regulatory framework should be developed to realise synergies between different product stewardship schemes for individual products, such as deposit-refund and other EPR schemes. By integrating different schemes with new digital technologies, such as smart tagging, the (transparency on) performance and mutual reinforcement would improve. Regulatory measures should include clear positive feedback for increasing recycled content and/or reuse.

- **Facilitate gathering and sharing of information and data on collection, sorting and recycling performance and best practices, to enable cross-value-chain collaboration and compatibility.** Guided by best practice, such a system should lead to simplification, standardisation and reduction of variability at all levels across the cycle of innovation: manufacturing, retail, use, pre-sorting, collection, sorting and (organic) recycling. Such an information sharing mechanism should also facilitate the interface between different sectors and foster a new cross-sectoral symbiosis (e.g. packaging to automotive or electronic equipment).

7. Mechanical Recycling

- **Develop regulatory and financial incentives to stimulate demand for recycled content.** Such market signals can be expected to drive investment and innovation towards improved recycling yields and quality. Rebalancing the true cost of virgin plastics, including environmental and social impacts, can improve the competitiveness of recycled plastics. Measures could include targets for recycled content and quality of recycled material, VAT reduction for use of recycled plastics, and different EPR fees for virgin versus recycled content. A first step could be to set and enforce high recycled content rates for non-food and other less sensitive applications.

- **Develop regulatory and financial incentives to drive product design towards products that can be effectively reused or recycled where they are put on the market (e.g. in PPWD, Ecodesign Directive and WFD).** Promote significant reduction in complexity and overengineering in application design while fulfilling performance requirements. Regulatory measures should drive innovations that are harmonised with, and not disruptive to, the recycling system, In addition, they should be updated regularly to reflect the current state and future trends, e.g. anticipating the presence of chemical tracers or other markers in plastics. Certification and labelling should help to boost uptake of recycled content, being part of wider quality assurance and communication efforts.

- **Develop and implement more holistic methodologies to assess the economic, environmental and social impacts of different after-use pathways for used plastics to inform design and decision-making.** Robust and comprehensive assessment tools should overcome the limitations of current LCA approaches, extending the assessment capabilities to socioeconomic and technical performance considerations, going beyond energy consumption and GHG emissions.

- **Set up a cross-value-chain platform with participation incentives to gather and share information and data on the material composition of primary and secondary plastics, to support industrial symbiosis and to determine the (future) role of mechanical recycling.** The information exchange should improve transparency on material composition, helping control unwanted substances and enabling value retention. It would require procedures, standards (existing and new) and transparency, and could be carried out in collaboration with international organisations, such as UN Comtrade. Such a platform should help connect supply and demand of used and recycled plastics. It should also facilitate debates on the role of mechanical recycling in a circular economy for plastics in the short- and long-term, complementing other after-use pathways, and based on the latest technical, behavioural and economic insights.

- **Set up guidelines on how to improve the performance of recycled plastics over time, including treatment and decontamination of legacy materials and hazardous substances.** The technical performance and minimisation of risks of recycled plastics should be reinforced by emphasis and transparency on decontamination during recycling (see, for example, FCMs regulation). Guidelines should help decide how to handle legacy substances, and avoid the presence of chemicals of concern in new products, of which brominated flame retardants form an important category. Assess the need to develop and implement standards for quality of after-use plastic after sorting for verification of recycling options (e.g. mechanical or chemical reprocessing), depending on intended application (e.g. food versus non-food packaging)

8. Chemical recycling

- **Provide regulatory and fiscal incentives to stimulate demand for recycled plastics, including public procurement and accounting for the costs of negative externalities linked to different primary feedstocks.** Fiscal incentives could include reduced VAT or lowered EPR fees, and regulatory measures could include a time-bound target for specific rates of recycled content. Measures need to be harmonised with planned or anticipated expansion of mechanical and chemical recycling capacity. If technical performance is equal, choice between virgin and secondary feedstock is driven mainly by cost, which effectively gives fossil-based plastics a discount versus recycled plastics, as the cost of negative externalities are not, or only partly, internalised. Public procurement should be considered as a tool for boosting the market for recycled content.

- **Develop and implement harmonised standards for the quality of mechanically and chemically recycled plastics and for the verification of recycled content, taking into account safety and application areas.** The latter could, for example, be based on a mass-balance approach. Valorisation of chemical recycling technologies in terms of better properties of the recycled material compared to mechanical recycling is needed to ensure scale-up. Therefore, recognition of the added value of chemical recycling compared to mechanical recycling should be clarified. Such standards could be linked to the development of tradable certificates proving that certain plastics are recycled or generated using recycled or renewable content, and possibly renewable energy.

- **Develop a vision for a holistic after-use system in Europe, incorporating reuse, mechanical, chemical and organic recycling, and develop a methodology for comparing these different options based on environmental, economic and social impacts, and feasibility.** Such a vision should clearly describe how scaling up these business models or technologies enables the EU to reach its recycling targets, as well as create a virtuous circle where higher-quality recycled materials lead to further increases in recycled content in plastics. The vision should also clarify the potential role of pyrolysis and gasification, including boundary conditions (e.g. related to energy requirements and application of the output). The methodology should include a standardised assessment framework to help understand the potential contribution of different pathways towards a circular economy, including recycling targets.

- **Review and update waste legislation to include the latest recycling technologies.** This adaptation should include the implementation of technical standards to ensure virgin-grade recycled polymers can be used in the same applications as corresponding virgin polymers.

9. Organic recycling and biodegradation

- **Develop a legal framework for communication about compostability and biodegradability, and provide clear information and business guidance on the different after-use pathways, and their complementarity.** Claims made should be sufficiently specific (e.g. including a reference to the specific environmental habitat) and based on the appropriate information validated by a third party (i.e. certification). Information sharing should be organised at European level, and include the education of citizens and business alike. Support should be redirected from mainly technical guidance to support at the level of communication and education.

- **Harmonise policymakers' efforts across Europe to provide a clear direction for R&I and implementation of compostable or biodegradable materials and their after-use pathways.** Authorities often have a dual approach, reflected for example through financial support for R&I in compostable plastics, but lacking a coherent regulatory framework or infrastructure investment for its implementation.

- **Invest in infrastructure to expand biological waste collection and treatment capacity in order to harmonise and simplify collection systems, including clarity on disposal of compostable materials.** Organic recycling of these resources would help retain their value in our economy (e.g. nutrients and minerals) and help increase the level of organic matter in the soil, which brings benefits for agro-technical reasons. The current capacity of industrial composting and anaerobic digestion needs to be increased to deal with larger volumes of organic waste. Compostable plastics and packaging can play a beneficial role by helping collect a higher share of moist food and kitchen waste.

- **Develop a methodology to compare the environmental, social and economic impacts of different after-use pathways enabled through material selection for a range of common products, and take regulatory measures accordingly.** Such a methodology should provide objective decision criteria to evaluate different after-use options (e.g. mechanical, chemical and organic recycling). Depending on the assessment outcome, use of compostable/biodegradable material could be recommended or made mandatory, or be discouraged or prohibited.

- **Develop standards, including on anaerobic digestion and on biodegradability in various environments, and harmonise the organisation of different standards, also exploring a horizontal organisation.** Building on existing efforts, develop additional standards for specific applications. For example, there is no specific European or international standard on acceptance criteria for plastics or packaging in anaerobic digestion. Currently, standards are written for material or product categories, while for environmental purposes they should be organised from the viewpoint of each environment.

APPENDIX: OVERVIEW R&I PRIORITIES

The following R&I priorities have been proposed by the experts based on the state of play, and challenges and knowledge gaps gathered through reviewed projects, available public knowledge and their own expertise. The R&I priorities have subsequently been synthesised and edited following feedback from a wider stakeholder group.

TOPIC	COMMENTS
1. Plastic pollution	
R&I in combining an understanding of the impact drivers of plastic pollution with the development and assessment of solutions	This approach supports sound decision making during design phase based on impact.
Research on sources, pathways and distribution of plastic pollution in different ecosystems	Often neglected eco-systems (deep sea, soil and air) should be included.
Research on the impact of plastic debris on human and environmental health	Current LCA methodologies should be expanded by assessing the impact on human and environmental health.
Research on social and behavioural aspects of plastic pollution	Interdisciplinary research has specific barriers that make it unclear if they should be tackled at EU level.
Innovation in methodologies and technologies for monitoring plastic debris	Monitoring should be set up with the goal of supporting risk assessment. Monitoring should happen at global scale.
Research on the development of a risk assessment for plastic pollution	This research should follow a precautionary approach. This research should enable prioritisation of risks, and guide implementation of appropriate solutions.
Research on the degradation of plastics and the leaching of chemicals into the environment	Research in this area should not only focus on the number of studies, but also on reliability.
2. Substances of concern to human and environmental health	
Innovation in designing, producing, using or reprocessing plastics that eliminate or minimise dispersion of hazardous chemicals into the environment	This innovation requires data on volume and characteristics of different chemicals used in plastics (monomers, polymers and additives) from the industry.
Research on the development of a framework for identification of better safe-by-design alternatives to current materials or products that raise concerns	Focus areas should be developed based on chemical groups, rather than individual chemicals. This research should be linked to market places and existing tools/lists that support the uptake of safer alternatives.
Innovation in safer finished (plastic) articles	Innovation should take into account all design elements of a finished article (e.g. inks, labels and adhesives) and its intended production, use and after-use pathway.
Research on the development of standardised detection methods for microplastics and nanoplastics, and standardised approaches to determine the risk of human exposure to these particles	This research should help to increase understanding of the (potential) impact, which should inform decision making.
Research on quick and affordable methods to detect contaminants in used or recycled plastics	These methods support value retention in the value chain through transparency on material content.

TOPIC	COMMENTS
3. New materials	
Innovation in redesign of plastic products to facilitate reuse, collection, sorting and recycling	‘Redesign’ needs a broad interpretation covering business model, product design and material choice.
Research on the development of educational programmes and support of multidisciplinary exchanges in material innovation	This research should identify capabilities and methodologies to instruct new generations.
Research on alternative plastics processing technologies that enable value retention	Multiple technologies have been developed, but they are often stuck at the pilot phase. Use of computational algorithms and renewable energy should be encouraged in such developments.
R&I in developing plastics derived from gaseous waste (e.g. CO_2, CO and methane)	R&I should overcome the high consumption of energy during conversion processes, amongst other challenges.
Innovation in replacing thermoset and cross-linked plastics unless safe and cost-effective recycling is available	Alternative materials should be safely and cost-effectively recyclable while bringing similar benefits.
Research on the development of biomimicry solutions	This research benefits from clearer communication on biomimicry aspects and potential.
Research on holistic LCA models for new material development	A broader range of criteria should be included: use of energy, water, raw materials, land, impact on biodiversity, equity and pollution. Models should be transparent on assumptions.
4. Biological feedstock	
Industry-scale piloting of specific bio-based plastics and chemicals	These pilots should provide insights for further commercialisation.
R&I in bio-based plastics and chemicals derived from widely available by-products of agriculture or forestry	R&I should take into account technical specifications, potential applications and their life cycle, infrastructure, and regulation to foster commercialisation.
R&I in mass-balance processes/tools	R&I should foster the use of renewable feedstock in existing chemical production sites. R&I could inform the development of a standard.
5. Business models, product and service design	
R&I in (digital technologies for) product design to improve mechanical, chemical or organic recycling	A clear overview of the large amount of existing knowledge should inform this research.
Research on the connection between citizen behaviour and the impact of policy (e.g. regarding collection) at local and European level	
R&I in information transparency across the value chain regarding the type of data required, its secure management, and enabling technologies (e.g. digital product passports, tracers and markers)	Research should cover potential applications of blockchain.
Innovation in (digital technologies for) product design to improve disassembly and separation	This innovation requires cross-value chain collaboration. Innovation should aim for simplicity, so ensure digital technologies are only used when real value is added.

TOPIC	COMMENTS
Innovation in user-centred design of products and business models based on behavioural insights	Research should cover feasibility and impact of reuse models and of closed-loop systems for different products.
Research on the benefits and success drivers of business models using decentralised production	Research should cover the role of supply-chain set-up and length.
Research on performance and integration of different EU product policies addressing plastics	Research should cover integration and complementarity of ecodesign, EPR, Green Public Procurement and ecolabel.
Research on the barriers and risks of a transition to a circular economy for plastics (e.g. linear models hindering uptake of circular ones, rebound effect)	Research should link changes in product, business model or company level to the wider economic vision for CE. Research should inform proactive decision making to mitigate identified risks and overcome identified barriers.
6. Collection and sorting	
Innovation in development of (digital) technologies to improve sorting, both large and small scale, and decontamination of collected plastics	Innovation needs to increase sorting depth, including films and smaller or lighter items.
Innovation in development of (digital) technologies to improve tagging and identification	Innovation should include a system for sharing material/component/product information to provide transparency across the value chain. Role and responsibility of the citizen needs to be considered, including use of incentives.
Innovation in development of (digital) technologies to improve pre-sorting, collection systems, and synergies between manual and automated collection and sorting	Innovation needs to produce open-source technologies to facilitate rapid and wide adoption. Innovation needs to take into account structure of global supply chains (e.g. international transport of used plastics).
Research on implications of implementing different EPR schemes (including deposit-refund systems) and the related infrastructure needs	
Innovation in methodologies to accurately quantify and forecast the generation rate and source of emerging waste composition	Solution should take into account both domestic production and imports. Solution should work at local level, and allow integration towards EU level.
Innovation in digital technologies that engage citizens to eradicate litter and improve collection	Innovation should cover dependency on local factors to understand scaling potential across EU.
Research on interdisciplinary solutions to handle and reduce plastics landscape complexity, incorporating social and behavioural insights	Solutions should take into account intended functionality, use and after-use pathway. Direction can be provided through EPR with modulated fees.
Research on redesign of home, commercial and institutional environment architecture and infrastructure provisions to optimise value retention (e.g. pneumatic or underground storage with robotic collection)	Research should take into account cost aspect, and potential to gradually phase in (e.g. through new building requirements).
7. Mechanical recycling	
Innovation in technologies and mechanisms that improve the quality of mechanically recycled polymers and the cost-effectiveness of the process	Innovation should be complementary to design changes as output quality is highly dependent on input quality.

TOPIC	COMMENTS
Innovation in solutions that reduce plastics landscape complexity to improve recycling	Innovation should address all technical aspects of currently increasing complexity, including multimaterials, polymer grades, additives and pigments. Innovation should be linked to supporting policies such as EPR systems, standardisations and ecodesign.
Industry-scale piloting of decontamination technologies	Technologies should cover limited predictability of presence of contaminants in processed material.
Research in the mechanisms, routes and systemic reasons for the successful use of recycled plastics in certain applications, and its replication potential	Research should include success cases from the demand side, as the supply side information may be limited due to IP issues.
R&I in standardised methods to verify recycled content in plastics	R&I should inform standardisation in this field.
Research on the dynamics of globalised secondary material supply chains	Research should focus on EU first to support achieving the recycling targets.
R&I in reduction of the environmental footprint of recycling facilities	R&I should cover material loss, water use, energy consumption and GHG emissions, from both quantitative and qualitative angle.
8. Chemical recycling	
Innovation in redesigning products and materials that improve efficiency and effectiveness of mechanical and chemical recycling	Redesign should suit both mechanical and chemical recycling, while the latter might be less sensitive to contaminants.
Industry-scale piloting of solvent-based purification and depolymerisation	Funded pilots should disseminate results and expose unanswered questions to inform general overview. Co-financing should be considered as bank guarantees are considered valuable.
Research on the economic, social and environmental impact of chemical recycling	Research should inform common terminology and definitions, and strategic decision on the role of chemical recycling.
Research on depolymerisation and solvent-based purification of common polymers	Research efforts should be balanced with volume of after-use streams for different (non-)packaging applications.
Research on systems optimisation by combining different plastics recycling technologies	Research should inform decision making on (infrastructure) investments and policies across different regions.
9. Organic recycling and biodegradability	
R&I in compostable and biodegradable materials for specific environments	R&I should be tailored to specific products and applications.
Research on the impact and feasibility of different after-use options for specific products and applications	Research should inform design and production, policymaking and (infrastructure) investments. Feasibility and impact depend on cross-value-chain collaboration linking design and after-use pathways.
Research in process-approval parameters for standards for organic recycling and biodegradation in specific environments	

APPENDIX: THE REPORT WRITING PROCESS

The European Commission is committed to evidence-based policymaking and exploiting valuable research and innovation results to their full potential. Therefore, this report has been written by extending a Projects-for-Policy approach. Projects-for-Policy is an initiative that aims to use research and innovation project results to shape policymaking (European Commission). The research and innovation projects funded by the EU Framework Programmes deliver results that are used for economic and social activities, as a basis for further research, or to develop new and better products and services. In addition, project results can provide valuable evidence for policy development and design, highlight gaps or barriers in current policy frameworks or approaches, and help develop new opportunities and innovative activities for any area of policymaking across Europe and the world.

The aim of a Projects-for-Policy initiative is to reinforce the role of EU-funded research and innovation projects and their concrete contributions to thematic policy. This report also aims to strengthen the policy-science interface work by drawing recommendations for sectoral policies and by identifying research and innovation needs to inform future EU R&I funding decisions, in particular in the area of plastics and the circular economy. To that end, it presents policy recommendations and priorities for research and innovation in the area of plastics and the circular economy, together with the underlying evidence extracted from EU-funded projects or publicly available sources. The results of the report will be disseminated across policy DGs of the European Commission, EU institutions, Member States and other relevant policy stakeholders.

The insights in this report were derived by selected experts reviewing plastics-related projects from FP6, FP7 and Horizon2020, and analysing their outcomes, based on policy questions that were developed by a range of policymakers. The experts complemented these findings on the current state of play, and on challenges and knowledge gaps with their own expertise and publicly available information (such as academic literature and publicly available reports, trade press and market data). They subsequently identified research and innovation needs and policy recommendations. In addition, the wider stakeholder group has been consulted in writing (from 30 August to 12 October 2018) and during a workshop (organised 3-4 October 2018), resulting in a large body of constructive feedback on the experts' work. Participants included industry actors from across the plastics value chains, academia, innovators, NGOs and policymakers.

The involved experts include Maurizio Crippa (gr3n, Switzerland), Bruno De Wilde (Organic Waste Systems, Belgium), Rudy Koopmans (Plastics Innovation Competence Centre, Switzerland), Jan Leyssens (Switchrs, Belgium), Mats Linder (CE expert, Sweden), Jane Muncke (Food Packaging Forum Foundation, Switzerland), Anne-Christine Ritschkoff (VTT Technical Research Centre of Finland, Finland), Karine Van Doorsselaer (Antwerp University, Belgium), Costas Velis (University of Leeds, the UK), and Martin Wagner (Norwegian University of Science and Technology, Norway).

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APPENDIX: OVERVIEW OF REVIEWED EU-FUNDED PROJECTS

Framework Programme	Project Number	Project Acronym	Project Title
FP7	315688	ADCELLPACK	Advanced cellulose packaging
H2020	720719	AGRIMAX	Agri and food waste valorisation co-ops based on flexible multi-feedstocks biorefinery processing technologies for new high added value applications
FP7	245084	ANIMPOL	Biotechnological conversion of carbon containing wastes for eco-efficient production of high added value products
H2020	726618	ARENA	The first on-site mobile solution for complete synthetic grass recycling and materials reuse
FP7	606572	BANUS	Definition and development of functional barriers for the use of recycled materials in multilayer food packaging
H2020	745578	BARBARA	Biopolymers with advanced functionalities for building and automotive parts processed through additive manufacturing
FP7	606144	BIO4MAP	Transparent and high barrier biodegradable film and sheet for customized Modified Atmosphere food Packaging.
H2020	723070	BIO4PRODUCTS	4x4, demonstrating a flexible value chain to utilize biomass functionalities in the processing industry
H2020	685614	BIO4SELF	Biobased self-functionalised self-reinforced composite materials based on high performance nanofibrillar PLA fibres
FP7	606548	BIOACTIVELAYER	Active and biodegradable multilayer structure for dehydrated or dried food packaging applications
FP7	315313	BIO-BOARD	Development of sustainable protein-based paper and paperboard coating systems to increase the recyclability of food and beverage packaging materials
FP7	312100	BIOCLEAN	New BIOtechnologiCaL approaches for biodegrading and promoting the environmEntal biotrAnsformation of syNthetic polymeric materials
H2020	720326	BIOCOMPLACK	Eco-friendly food packaging with enhanced barrier properties
FP7	289194	BIOCONSEPT	Integration of Bio-Conversion and Separation Technology for the production and application of platform chemicals from 2nd generation biomass
H2020	737741	BIOMULCH	Integrated solution for innovative biodegradation control of agricultural plastic mulches
FP7	613941	BIO-QED	Large scale demonstration for the bio-based bulk chemicals BDO and IA aiming at cost reduction and improved sustainability
FP7	613771	BIOREFINE-2G	Development of 2nd Generation Biorefineries – Production of Dicarboxylic Acids and Bio-based Polymers Derived Thereof
H2020	745762	BIOSMART	Bio-based smart packaging for enhanced preservation of food quality.

Framework Programme	Project Number	Project Acronym	Project Title
FP7	311935	BRIGIT	New tailor-made biopolymers produced from lignocellulosic sugars waste for highly demanding fire-resistant applications
FP7	246449	BUGWORKERS	New tailor-made PHB-based nanocomposites for high performance applications produced from environmentally friendly production routes
H2020	732389	CAPID	Capacitive Identification Tokens
H2020	768919	CARBON4PUR	Turning industrial waste gases (mixed CO/CO_2 streams) into intermediates for polyurethane plastics for rigid foams/building insulation and coatings
H2020	679050	CELBICON	Cost-effective CO_2 conversion into chemicals via combination of Capture, ELectrochemical and BI-ochemical CONversion technologies
H2020	730423	CIRC-PACK	Towards circular economy in the plastic packaging value chain
FP7	308370	CLEANSEA	Towards a Clean, Litter-Free European Marine Environment through Scientific Evidence, Innovative Tools and Good Governance
H2020	673663	CLIPP PLUS	Manufacture and commercialisation of high-quality recycled polyolefin films using an innovative continuous extrusion recycling process assisted by sc-CO_2 for printed plastic waste
H2020	641747	CloseWEEE	Integrated solutions for pre-processing electronic equipment, closing the loop of post-consumer high-grade plastics, and advanced recovery of critical raw materials antimony and graphite
FP7	614155	COMMON SENSE	Cost-effective sensors, interoperable with international existing ocean observing systems, to meet EU policies requirements
FP6	13871	CONCLORE	Controlled Closed Loop Recycling for Life-Cycle Optimised Industrial Production
H2020	635405	COSMOS	Camelina & crambe Oil crops as Sources for Medium-chain Oils for Specialty oleochemicals
H2020	696324	CSA OCEANS 2	Coordination action in support of the implementation of the Joint Programming Initiative on ‘Healthy and Productive Seas and Oceans’
FP7	304987	DEGRICOL	Consumer-safe and thermally-stable bioplastic formulation with controlled biodegradation properties for agricultural and horticultural accessories
H2020	768573	DEMETO	Modular, scalable and high-performance DE-polymerization by MicrowavE TechnolOgy
FP7	280786	ECLIPSE	Renewable eco-friendly poly(lactic acid) nanocomposites from waste sources
FP7	309701	ECO2CO2	Eco-friendly biorefinery fine chemicals from CO_2 photo-catalytic reduction
FP7	298619	ECOLASTANE	A novel technology for producing bio-based synthetic textile fibres from biomass-derived furanic monomers
FP7	315009	ECOPET	Demonstration of innovative, lightweight, 100% recyclable PET prototype formulations and process tooling for low carbon footprint packaging to replace current industry standard virgin plastics

Framework Programme	Project Number	Project Acronym	Project Title
H2020	634880	EDC-MIXRISK	Integrating Epidemiology and Experimental Biology to Improve Risk Assessment of Exposure to Mixtures of Endocrine Disruptive Compounds
H2020	723867	EMMC	The aim of this CSA is to establish current and forward-looking complementary activities necessary to bring the field of materials modelling closer to the demands of manufacturers in Europe.
H2020	720297	ENZOX2	New enzymatic oxidation/oxyfunctionalisation technologies for added value bio-based products
H2020	633172	EUROMIX	Development of an experimentally verified, tiered strategy for the risk assessment of mixtures of multiple chemicals derived from multiple sources across different life stages.
FP7	604770	EUROPHA	Novel technology to boost the European Bioeconomy: reducing the production costs of PHA biopolymer and expanding its applications as 100% compostable food packaging bioplastic
H2020	681002	EU-TOXRISK	An Integrated European 'Flagship' Program Driving Mechanism-based Toxicity Testing and Risk Assessment for the 21st Century
FP7	228867	F3FACTORY	Flexible, Fast and Future Production Processes
H2020	730323	FiberEUse	Large scale demonstration of new circular economy value-chains based on the reuse of end-of-life fiber reinforced composites
FP7	298171	FIBIOSEAT	FIre resistant BIObased polyurethane foam for aircraft SEATing cushions
H2020	669029	FIRST2RUN	Flagship demonstration of an integrated biorefinery for dry crops sustainable exploitation towards biobased materials production
H2020	642154	FISSAC	Fostering industrial symbiosis for a sustainable resource intensive industry across the extended construction value chain
FP7	207810	FLEXPAKRENEW	Design and development of an innovative ecoefficient low-substrate flexible paper packaging from renewable resources to replace petroleum-based barrier films
H2020	713475	FLIPT	FLow Induced Phase Transitions, A new low energy paradigm for polymer processing
FP7	212239	FORBIOPLAST	Forest Resource Sustainability through Bio-Based-Composite Development
H2020	689157	FORCE	Cities Cooperating for Circular Economy
FP7	309283	FREEFOAM	Novel PUR foaming manufacturing process with reduced toxic isocyanate content
H2020	720739	FRESH	Fully bio-based and bio-degradable ready meal packaging
H2020	660306	FreshwaterMPs	The environmental fate and effects of microplastics in freshwater ecosystems
H2020	720720	FUNGUSCHAIN	Valorisation of mushroom agrowastes to obtain high value products
FP7	605698	GREEN PACK	Fully recyclable 100% PET package for food contact with O_2 barrier, improved transparency and low CO_2 footprint.

Framework Programme	Project Number	Project Acronym	Project Title
H2020	304478	HAYNEST	Biodegradable 3D package material based on organic residues
H2020	733032	HBM4EU	European Human Biomonitoring Initiative
H2020	720736	HYPERBIOCOAT	High performance biomass extracted functional hybrid polymer coatings for food, cosmetic and medical device packaging
H2020	718922	IFOODBAG GEN2	Unique, low-cost, low-footprint, reusable hybrid carrier bag system that enables food to be kept cold/frozen for up to 24 hours
FP7	308465	INNOBITE	Transforming urban and agricultural residues into high performance biomaterials for green construction
FP7	309802	INNOREX	Continuous, highly precise, metal-free polymerisation of PLA using alternative energies for reactive extrusion
FP7	265212	IRCOW	Innovative Strategies for High-Grade Material Recovery from Construction and Demolition Waste
H2020	723268	KARMA2020	Industrial Feather Waste Valorisation for Sustainable KeRatin based MAterials.
FP7	315241	LEGUVAL	Valorisation of legumes co-products and by-products for package application and energy production from biomass
FP7	280387	MEATCOAT	Development of a new functional antimicrobial edible film for fresh meat products
FP7	604279	MMP	Multiscale Modelling Platform: Smart design of nano-enabled products in green technologies
FP7	280759	NANOBARRIER	Extended shelf-life biopolymers for sustainable and multifunctional food packaging solutions
FP7	262387	NANOCORE	Development of a low FST and high mechanical performance nanocomposite foam core material for ferries and cruise ship superstructures
FP7	243725	NANOFLEX	A universal flexible low-cost plumbing and heating pipe system fully environment-compatible by using innovative nanoparticle technology
FP7	618560	NANOPLAST	A computational study of the interaction between nanoplastic and model biological membranes
FP7	605658	NATURTRUCK	Development of a new Bio-Composite from renewable resources with improved thermal and fire resistance for manufacturing a truck internal part with high quality surface finishing
FP7	315233	N-CHITOPACK	Sustainable technologies for the production of biodegradable materials based on natural chitin-nanofibrils derived by waste of fish industry, to produce food grade packaging
H2020	642231	New_Innonet	The Near-zero European Waste Innovation Network
FP7	280604	OLI-PHA	A novel and efficient method for the production of polyhydroxyalkanoate polymer-based packaging from olive oil waste water
FP7	613677	OPEN-BIO	Opening bio-based markets via standards, labelling and procurement

Framework Programme	Project Number	Project Acronym	Project Title
H2020	633962	P4SB	From Plastic waste to Plastic value using *Pseudomonas putida* Synthetic Biology
H2020	738808	PAPTIC	The Good Conscience Alternative
FP7	246776	PARADIGM	New Paradigm in the Design of Degradable Polymeric Materials - Macroscopic Performance Translated to all Levels of Order
H2020	744409	PEFERENCE	From bio-based feedstocks via di-acids to multiple advanced bio-based materials with a preference for polyethylene furanoate
FP7	265397	PEROXICATS	Novel and more robust fungal peroxidases as industrial biocatalysts
FP7	280831	PHBOTTLE	New sustainable, functionalized and competitive PHB material based in fruit by-products getting advanced solutions for packaging and non-packaging applications
FP7	310187	PHOENIX	Synergic combination of high performance flame retardant based on nano-layered hybrid particles as real alternative to halogen based flame retardant additives
FP7	211473	PLASMANICE	Atmospheric Plasmas for Nanoscale Industrial Surface Processing
H2020	730292	PLASTICIRCLE	Improvement of the plastic packaging waste chain from a circular economy approach
FP7	311777	POLYMARK	Novel Identification Technology for High-value Plastics Waste Stream
FP7	283707	POLY-SOLVE	Development of a selective, green solvent-based recovery process for waste polystyrene and polycarbonate
H2020	809308	R3FIBER	Eco-innovation in Composites Recycling for a Resource-Efficient Circular Economy
H2020	723670	REHAP	Systemic approach to Reduce Energy demand and CO_2 emissions of processes that transform agroforestry waste into High Added value Products.
H2020	730053	REINVENT	Realising Innovation in Transitions for Decarbonisation
H2020	691414	ReTAPP	Re-Think All Plastic Packaging
H2020	733676	REW-TYRES	Innovative and compact process for recycling rubber suitable to improve the environmental footprint of the tyre industry over the life-cycle
FP7	226552	RISKCYCLE	Risk-based management of chemicals and products in a circular economy at a global scale
H2020	673690	ROBOLUTION	Robotic Recycling Revolution
FP7	606032	SEABIOPLAS	Seaweeds from sustainable aquaculture as feedstock for biodegradable bioplastics
FP7	258203	SMART-EC	Heterogeneous integration of autonomous smart films based on electrochromic transistors
H2020	668467	SMARTLI	Smart Technologies for the Conversion of Industrial Lignins into Sustainable Materials
FP7	311956	SPLASH	Sustainable PoLymers from Algae Sugars and Hydrocarbons

Framework Programme	Project Number	Project Acronym	Project Title
H2020	645987	SPORT INFINITY	Waste-Based Rapid Adhesive-free Production of Sports goods
FP7	218335	START	Development of a Retro-Fitted Recycling Unit and Inter-Related Web-Based Logistical Software to Reduce Transport Costs and Improve Competitiveness of Organisations in the Recycling Supply Chain
FP7	289196	SUCCIPACK	Development of active, intelligent and sustainable food PACKaging using PolybutyleneSUCCInate
FP7	285889	SUPERCLEANQ	Development of processes and quality procedures for the valorisation of recycled plastics for food contact applications
FP7	289829	SUSFOFLEX	Smart and SUStainable FOod packaging utilizing FLEXible printed intelligence and materials technologies
H2020	680426	SYMBIOPTIMA	Human-mimetic approach to the integrated monitoring, management and optimisation of a symbiotic cluster of smart production units
FP7	311815	SYNPOL	Biopolymers from syngas fermentation
H2020	677471	TERRA	Tandem Electrocatalytic Reactor for energy/Resource efficiency And process intensification
FP7	289603	TRANSBIO	BioTRANSformation of by-products from fruit and vegetable processing industry into valuable BIOproducts
FP7	232176	ULTRAVISC	Sensor-Base Ultrasonic Viscosity Control for the Extrusion of Recycled Plastics
H2020	690103	URBANREC	New approaches for the valorisation of URBAN bulky waste into high added value RECycled products
FP7	212782	W2PLASTICS	Magnetic Sorting and Ultrasound Sensor Technologies for Production of High Purity Secondary Polyolefins from Waste
H2020	688995	WASTE4THINK	Moving towards Life Cycle Thinking by integrating Advanced Waste Management Systems
FP7	218340	WHEYLAYER	Whey protein-coated plastic films to replace expensive polymers and increase recyclability
FP7	315743	WHEYLAYER 2	Barrier biopolymers for sustainable packaging
H2020	720303	Zelcor	Zero Waste Ligno-Cellulosic Biorefineries by Integrated Lignin Valorisation

APPENDIX: LINK TO EU PLASTICS STRATEGY

The policy recommendations and R&I priorities in this report aim to support and complement the direction and measures mentioned in *A European Strategy for Plastics in a Circular Economy*. The first table below compares the measures identified in the EU Plastics Strategy with the recommendations in this report. The majority of measures are matched to recommendations, which provide additional details. When measures do not have a straightforward match, this seems due to their nature being different from R&I (e.g. 'renewed engagement on plastics/marine litter in fora such as the UN, G20, MARPOL, regional sea conventions'), or to the fact that the measure is a well-known ongoing or concluded action for which a recommendation would no longer be relevant (e.g. 'restrict intentional addition of microplastics to products via REACH'). The second table below lists the recommendations for which there is no direct match, for different reasons. These recommendations complement existing measures.

The European Strategy for Plastics in a Circular Economy		A circular economy for plastics *Insights from research and innovation to inform policy and funding decisions*	
Measure group	**Measure**	**Recommendations**	**Chapter**
Improving the economics and quality of plastics recycling	Preparatory work for a future revision of the Packaging & Packaging Waste Directive: initiate work on new harmonised rules to ensure that by 2030 all plastic packaging placed on the EU market can be reused or recycled in a cost-effective manner	▸ Develop product policies, standards and a holistic assessment methodology to assess and support the design of circular products, services and business models.	▸ Business models, product and service design
		▸ Develop regulatory and financial incentives to stimulate demand for recycled content.	▸ Mechanical recycling
Improving the economics and quality of plastics recycling	Improve the traceability of chemicals and address the issue of legacy substances in recycled streams	▸ Enforce, harmonise and adapt existing EU chemical regulations, including REACH, the Toy Safety Directive and the regulation on food-contact materials.	▸ Substances of concern to human and environmental health
		▸ Facilitate gathering and sharing of information and data on collection, sorting and recycling performance and best practices, to enable cross-value-chain collaboration and compatibility.	▸ Collection and sorting
		▸ Set up guidelines on how to improve performance of recycled plastics over time, including treatment and decontamination of legacy materials and hazardous substances.	▸ Mechanical recycling

Measure group	Measure	Recommendations	Chapter
Improving the economics and quality of plastics recycling	New ecodesign requirements to support the recyclability of plastics	▸ Develop and implement regulatory incentives such as extended producer responsibility systems and shared responsibilities across the value chain to steer (plastic) product design towards reuse and cost-effective recycling. ▸ Develop regulatory measures and incentives such as EPR systems, ecodesign and minimum product requirements to steer product design towards elimination, use of renewable or recycled feedstock, reuse and cost-effective recycling (Packaging and Packaging Waste, Ecodesign, and Waste Framework Directive). ▸ Develop regulatory measures, such as a stewardship framework or EPR with modulated fees, integrating new digital technologies, to cover costs of waste collection and processing, to incentivise product design towards circular pathways, and to fund innovation in this field. ▸ Develop regulatory and financial incentives to drive product design towards products that can be effectively reused or recycled where they are put on the market (e.g. in PPWD, Ecodesign Directive and WFD).	▸ New materials ▸ Business models, product and service design ▸ Collection and sorting ▸ Mechanical recycling
Improving the economics and quality of plastics recycling	Launching an EU-wide pledging campaign targeting industry and public authorities	▸ Collaborate towards a common vision across the plastic value chains to trigger actions on regional, national, European and global level.	▸ General cross-value chain insights
Improving the economics and quality of plastics recycling	Assessment of regulatory or economic incentives in revision of Packaging waste; evaluation/review of the Construction Products Regulation; and evaluation/review of End-of-life Vehicles Directive	▸ Develop and implement regulatory incentives such as extended producer responsibility systems and shared responsibilities across the value chain to steer (plastic) product design towards reuse and cost-effective recycling. ▸ Develop regulatory measures and incentives such as EPR systems, ecodesign and minimum product requirements to steer product design towards elimination, use of renewable or recycled feedstock, reuse and cost-effective recycling (Packaging and Packaging Waste, Ecodesign, and Waste Framework Directive). ▸ Develop regulatory measures, such as a stewardship framework or EPR with modulated fees, integrating new digital technologies, to cover costs of waste collection and processing, to incentivise product design towards circular pathways, and to fund innovation in this field. ▸ Develop regulatory and financial incentives to drive product design towards products that can be effectively reused or recycled where put on the market (e.g. in PPWD, Ecodesign Directive and WFD).	▸ New materials ▸ Business models, product and service design ▸ Collection and sorting ▸ Mechanical recycling

Measure group	Measure	Recommendations	Chapter
Improving the economics and quality of plastics recycling	Food-contact materials: swift finalisation of pending authorisation procedures for plastics recycling processes better characterisation of contaminants and introduction of monitoring system	‣ Set up guidelines on how to improve performance of recycled plastics over time, including treatment and decontamination of legacy materials and hazardous substances.	‣ Mechanical Recycling
Improving the economics and quality of plastics recycling	Development of standards for sorted plastics waste and recycled plastics	‣ Develop regulatory and financial incentives to stimulate demand for recycled content.	‣ Mechanical Recycling
Improving the economics and quality of plastics recycling	Ecolabel and GPP: further incentivise the use of recycled plastics, including by developing adequate verification means	‣ Develop regulatory and financial incentives to stimulate demand for recycled content. ‣ Provide regulatory and fiscal incentives to stimulate demand for recycled plastics, including public procurement and accounting for the costs of negative externalities linked to different primary feedstocks. ‣ Develop and implement harmonised standards for quality of mechanically and chemically recycled plastics and for verification of recycled content, taking into account safety and application areas.	‣ Mechanical Recycling ‣ Chemical recycling ‣ Chemical recycling
Improving the economics and quality of plastics recycling	New guidelines on separate collection and sorting of waste	‣ Enforce waste legislation and develop regulatory framework to harmonise collection systems, allowing a certain degree of local adaptation to socioeconomic conditions.	‣ Collection and sorting
Improving the economics and quality of plastics recycling	Ensure better implementation of existing obligations on separate collection, including through ongoing review of waste legislation	‣ Enforce waste legislation and develop regulatory framework to harmonise collection systems, allowing a certain degree of local adaptation to socioeconomic conditions.	‣ Collection and sorting
Curbing plastic waste and littering	Legislative proposal on port reception facilities		
Curbing plastic waste and littering	Development of measures to reduce loss of fishing gear: legislative instrument on single use plastics and fishing gear	‣ Develop product policies, standards and a holistic assessment methodology to assess and support the design of circular products, services and business models.	‣ Business models, product and service design
Curbing plastic waste and littering	Development of measures to limit plastic loss from aquaculture (e.g. BREF document)		

Measure group	Measure	Recommendations	Chapter
Curbing plastic waste and littering	Improved monitoring and mapping of marine litter	‣ Harmonise definitions, frameworks for systematic data gathering, and analyses of plastic flows and pollution at European and global level. ‣ Develop open collaboration platforms to enable more comprehensive analyses and frequent benchmarking on plastic flows and impacts, to provide information on and for investments, and to create political and public will.	‣ Plastic pollution ‣ Plastic pollution
Curbing plastic waste and littering	Support MS with the implementation of their POM's under the MSFD and links with waste/litter management plans under the WFD		
Curbing plastic waste and littering	Develop harmonised rules on defining and labelling compostable and biodegradable plastics	‣ Develop a legal framework on communication about compostability and biodegradability, and provide clear information and business guidance on the different after-use pathways, and their complementarity.	‣ Organic recycling and biodegradation
Curbing plastic waste and littering	Lifecycle assessment to identify conditions where use of compostable and biodegradable plastics is beneficial, and criteria for such application	‣ Develop and implement more holistic methodologies to assess the economic, environmental and social impacts of different after-use pathways for used plastics to inform design and decision-making. ‣ Develop a methodology to compare environmental, social and economic impact of different after-use pathways enabled through material selection for a range of common products, and take regulatory measures accordingly. ‣ Harmonise policymakers' efforts across Europe to provide a clear direction for R&I and implementation of compostable or biodegradable materials and their after-use pathways.	‣ Mechanical recycling ‣ Organic recycling and biodegradation ‣ Organic recycling and biodegradation
Curbing plastic waste and littering	Restrict use of oxo-plastics via REACH		
Curbing plastic waste and littering	Restrict intentional addition of microplastics to products via REACH		
Curbing plastic waste and littering	Policy options to reduce release of microplastics from tyres, textile, paint		
Curbing plastic waste and littering	Measures to reduce plastic pellet spillage		
Curbing plastic waste and littering	Evaluation of the UWWTD, assess effectiveness on microplastics capture and removal		

Measure group	Measure	Recommendations	Chapter
Driving investment and innovation towards circular solutions	Guidance on eco-modulation of EPR fees	▸ Develop and implement regulatory incentives such as extended producer responsibility systems and shared responsibilities across the value chain to steer (plastic) product design towards reuse and cost-effective recycling. ▸ Develop regulatory measures and incentives such as EPR systems, ecodesign and minimum product requirements to steer product design towards elimination, use of renewable or recycled feedstock, reuse and cost-effective recycling (Packaging and Packaging Waste, Ecodesign, and Waste Framework Directive). ▸ Develop regulatory measures, such as a stewardship framework or EPR with modulated fees, integrating new digital technologies, to cover costs of waste collection and processing, to incentivise product design towards circular pathways, and to fund innovation in this field. ▸ Develop regulatory and financial incentives to drive product design towards products that can be effectively reused or recycled where they are put on the market (e.g. in PPWD, Ecodesign Directive and WFD).	▸ New materials ▸ Business models, product and service design ▸ Collection and sorting ▸ Mechanical recycling
Driving investment and innovation towards circular solutions	Recommendations by the 'Circular Economy Finance Support Platform'	▸ Provide and enable funding and financial incentives for infrastructure and (long-term) R&I that maximises plastics value retention.	▸ New materials
Driving investment and innovation towards circular solutions	Feasibility of a private-led investment fund for innovation	▸ Provide and enable funding and financial incentives for infrastructure and (long-term) R&I that maximises plastics value retention.	▸ New materials
Driving investment and innovation towards circular solutions	Direct financial support through European Fund for Strategic Investments (EFSI) and other EU funding instruments	▸ Provide funding for research and financial incentives for systemic innovation across the plastics value chain. ▸ Provide and enable funding and financial incentives for infrastructure and (long-term) R&I that maximises plastics value retention. ▸ Provide regulatory, legal and financial incentives to support (long-term) R&I in and scale-up of innovative bio-based materials and chemicals towards a self-sustaining critical mass, guided by systems thinking. ▸ Set up, connect and participate as an active stakeholder or shareholder in investment instruments to enable investors and lenders to provide funds for circular economy business models.	▸ General cross-value-chain insights ▸ New materials ▸ Biological feedstock ▸ Business models, product and service design
Driving investment and innovation towards circular solutions	Life-cycle impacts of alternative feedstock for plastic production	▸ Provide regulatory, legal and financial incentives to support (long-term) R&I in and scale-up of innovative bio-based materials and chemicals towards a self-sustaining critical mass, guided by systems thinking.	▸ Biological feedstock

Measure group	Measure	Recommendations	Chapter
Driving investment and innovation towards circular solutions	Development of a Strategic Research and Innovation Agenda on plastics to guide future funding decisions	▸ This report forms a major input into the Development of the Strategic Research and Innovation Agenda	
Harnessing global action	Project to reduce plastic waste and marine litter in East and Southeast Asia		
Harnessing global action	Examining options for specific action to reduce plastic pollution in the Mediterranean (Barcelona Convention)		
Harnessing global action	Cooperation on plastic waste prevention in major world river basins		
Harnessing global action	Renewed engagement on plastics/marine litter in fora such as the UN, G20, MARPOL, regional sea conventions		
Harnessing global action	Support action under the Basel Convention, particularly for the implementation of the toolkit for environmentally sound waste management		
Harnessing global action	Promote a circular plastics economy in non-EU countries through policy dialogues on trade, industry and environment, as well as economic diplomacy	▸ Collaborate towards a common vision across the plastics value chains to trigger actions at regional, national, European and global level.	▸ General cross-value-chain insights
Harnessing global action	Use bilateral, regional and thematic funding in EU development, neighbourhood and enlargement policies		
Harnessing global action	Support the development of international industry standards for sorted plastic waste and recycled plastics	▸ Set up a cross-value-chain platform with participation incentives to gather and share information and data on material composition of primary and secondary plastics, to support industrial symbiosis and to determine the (future) role of mechanical recycling.	▸ Mechanical recycling
Harnessing global action	Ensure that exported plastic waste is dealt with appropriately, in line with the EU waste shipment regulation		
Harnessing global action	Support the development of a certification scheme for recycling plants in EU and third countries		

The following recommendations could not be directly matched on a one-to-one basis to measures mentioned in the EU Plastics Strategy for several reasons, such as being too broad or narrow, or taking a specific R&I perspective. In this way these recommendations complement the existing measures. While a direct match might not be straightforward, policymaking work on the following recommendations could already be ongoing or planned.

Recommendations	Chapter
Develop, harmonise and enforce regulatory and legal frameworks guided by systems thinking.	▸ General cross-value-chain insights
Set up, connect and fund mechanisms to coordinate the transition strategically and to invest in upstream and downstream capacity across Europe.	▸ General cross-value-chain insights
Educate and support citizens, companies and investors on the transition towards a circular economy for plastics.	▸ General cross-value-chain insights
Develop risk assessment and policy frameworks based on a systems thinking approach	▸ Plastic pollution
Develop regulatory frameworks with additional requirements for additives and other chemicals in plastic products based on the overall migrate and the potential toxicity of the mixture from combined exposure to finished articles.	▸ Substances of concern to human and environmental health
Provide business support and guidance to identify and reduce chemical hazards.	▸ Substances of concern to human and environmental health
Develop a platform for creating information transparency and for facilitating the sharing and trading of R&I, taking into account the sensitivity of certain information.	▸ New materials
Set up a coordination board for strategic long-term investments, combining technical, commercial and behavioural insights.	▸ New materials
Provide information for citizens and business about bio-based materials by developing standards, labels and a holistic impact assessment framework.	▸ Biological feedstock
Set up a strategic coordination board to develop EU-wide planning for production and after-use handling infrastructure and to track existing and expected inventories to drive scale-up of bio-based plastics and chemicals.	▸ Biological feedstock
Facilitate gathering and sharing of reliable information and data to foster open innovation by knowledge exchange between innovators, industry and the public to ensure activities such as circular design training and circular public procurement.	▸ Business models, product and service design
Incorporate a holistic, circular approach and thorough testing and prototyping of business models as requirements in R&I projects, allowing enough freedom for shifting scope, focus and content (Horizon Europe).	▸ Business models, product and service design
Incorporate systems thinking, circular economy and environmental impacts in the education curriculum at all levels to provide a solid knowledge base for future generations of designers and innovators.	▸ Business models, product and service design
Develop a vision for a holistic after-use system in Europe, incorporating reuse, mechanical, chemical and organic recycling, and develop a methodology for comparing these different options based on environmental, economic and social impacts, and feasibility.	▸ Chemical recycling
Review and update waste legislation to include the latest recycling technologies.	▸ Chemical recycling
Invest in infrastructure to expand biological waste collection and treatment capacity in order to harmonise and simplify collection systems, including clarity on disposal of compostable materials.	▸ Organic recycling and biodegradation
Develop standards, including on anaerobic digestion and on biodegradability in various environments, and harmonise the organisation of different standards, exploring a horizontal organisation.	▸ Organic recycling and biodegradation

APPENDIX: OVERVIEW PLASTICS AND ITS APPLICATIONS

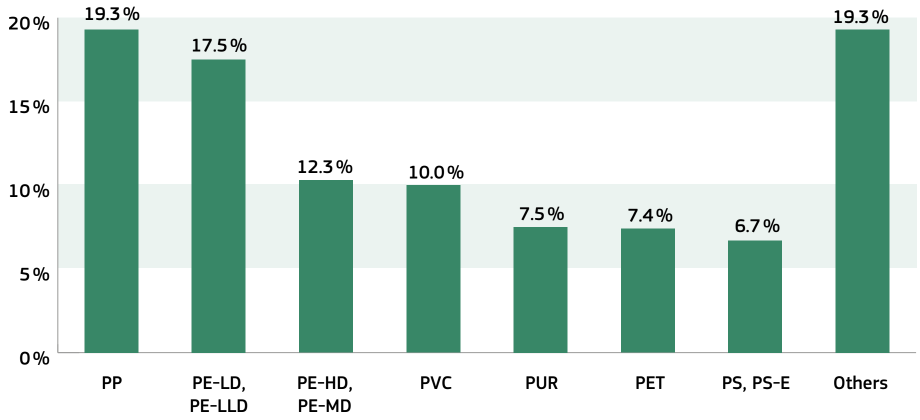
(*Most of the information in this appendix has been literally copied from* (Joint Research Centre, European Commission, 2014) and (European Commission, 2018c).)

A plastic material is an organic solid, essentially a polymer or combination of polymers of high molecular mass. A polymer is a chain of several thousand repeating molecular units of monomers. The monomers of plastic are either natural or synthetic organic compounds. The term 'resin' is sometimes used as synonym for a commercial polymer.

Plastics can be classified by chemical structure, i.e. by the main monomer of the polymer's backbone and side chains. Some important groups in these classifications are the acrylics, polyesters, polyolefins, silicones, polyurethanes and halogenated plastics. Plastics can also be classified by the chemical process used in their synthesis, such as condensation and cross-linking. Other classifications are based on properties that are relevant for manufacturing or product design, e.g. thermoplasticity, biodegradability, electrical conductivity, density and resistance to various chemical products. See Figure 26 for the European plastics converter demand by polymer types in 2016.

The vast majority of plastics are composed of polymers of carbon and hydrogen alone or with oxygen, nitrogen, chlorine, fluorine or sulphur in the backbone. More often than not, plastics contain a main polymer, and a bespoke load of additives to improve specific properties, e.g. hardness, softness, UV resistance, flame formation resistance, or their behaviour during manufacture (lubricants, catalysts, stabilisers, solvents, polymerisation aids and recycling aids). The content of additives in plastics varies widely, from less than 1 % in PET bottles to up to 50-60 % in PVC, often striking a balance between technical properties and economics, as some additives are considerably more expensive

Figure 26: European plastics converter demand by polymer types in 2016. Data for EU28+NO/CH



Source: PlasticsEurope, 2018

than the main polymers, while others are inexpensive (inorganic fillers such as limestone or talc). A non-exhaustive list of additive types is provided below:

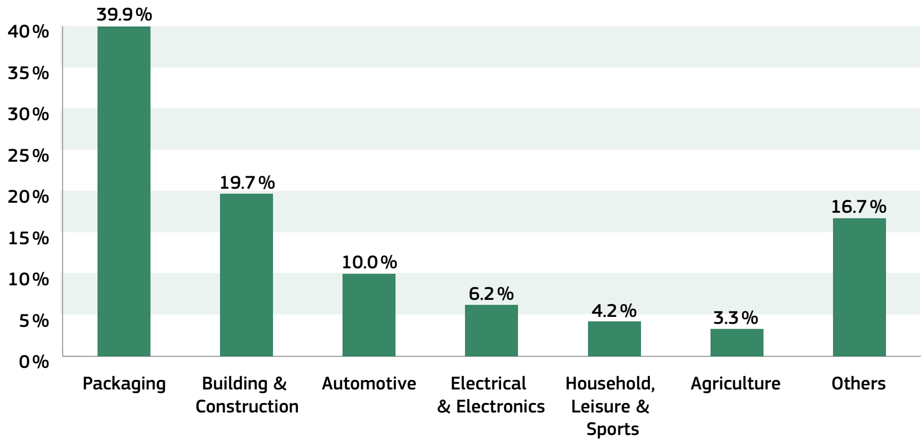
- Additives enhancing properties of the plastic product:
    - Stabilisers (acids, oxidation, biodegradation, heat, UV, etc.)
    - Flame retardants
    - Plasticisers
    - Colourants
    - Antifogging and antistatic agents
    - Optical brighteners, fluorescent whitening
    - Fillers and reinforcements/coupling agents
    - Impact modifiers

- Additives enhancing properties of the processing of plastics:
    - Lubricants
    - Nucleating agents
    - Polymer processing aids
    - Blowing agents
    - Additives for mechanical recycling of plastics (mainly re-stabilisers and compatibilisers)

Plastic articles are produced from the polymer, usually in powder, granulate, pellet or flake form, by a range of different processes, generally termed as 'conversion'. For example, rigid packaging such as bottles and drums use a moulding process where an extruded length of tube is inflated, whilst still above its softening point, into a mould which forms the shape/size of the container. Conversely, flexible packaging film is produced by extrusion techniques, such as casting, blowing or calendering, depending on the material and the thickness. The films are then usually printed with product (content) data and may also be laminated to other plastic films or non-plastic materials to provide improved functionality, e.g. rigidity, aroma impermeability, modified atmosphere packaging.

Plastic materials are used in a variety of applications (see Figure 27 for the plastics converter demand by segment).

Figure 27: **Distribution of European (EU28+NO/CH) plastics converter demand by segment in 2016**



Source: PlasticsEurope, 2018

In Europe, 57 million tonnes of primary plastics were produced in 2016. The European plastics industry is a big part of the chemicals industry and plays a vital role in the EU economy. It employs about 1.45 million people and has a turnover of EUR 350 billion (including plastic converters and technology providers). In 2013, the bioplastics industry accounted for around 23 000 jobs in Europe. Plastics recyclers account for some 30 000 jobs linked to the plastics industry. This general information can be detailed as follows.

- In 2014, in the EU-28, the manufacturing of plastic in primary forms (NACE C2016) employed more than 135 000 people in 2 600 firms. In terms of value added (at factor costs), the sector generated EUR 15 billion, i.e. the 0.9 % of total EU manufacturing (Eurostat). SMEs account for roughly 25 % of value added.
- The manufacturing of plastic products (NACE C222) employed some extra 1 300 000 people, distributed over 55 thousand firms, of which only 753 were not SMEs. About 20 % of the people are employed in the manufacturing of plastic packaging goods. In terms of value added, the sector generated EUR 64 billion, accounting for 3.7 % of total EU manufacturing (Eurostat).
- In 2014, about 17 700 firms with 164 000 employees were active in the recovery of sorted materials (NACE E3832). This category not only refers to the recovery of plastic, but also other materials such as paper and metal. Recovery of sorted materials generated nearly EUR 10 billion in value added. It is estimated that the number of SMEs is 17 200 firms, accounting for EUR 8.5 billion value added. Information on the specific share of plastic, however, is not available.

LIST OF DEFINITIONS AND ACRONYMS

The list below does not indicate a recommendation of a specific definition. Rather, the aim is to broadly explain some of the concepts used in this report. For some of these terms a related standard exists, or a detailed definition can be found in the relevant legislative documents.

Definitions

Anaerobic digestion (biogasification or biomethanisation): A process by which microorganisms break down biodegradable material in the absence of oxygen. The output is often a collection of energetic molecules such as methane, which can be used as fuel or for conversion to other chemicals.

Bio-based (of a feedstock, chemical or material): Made wholly or to a significant part from biomass. Does not define or limit the amount of energy or conversion steps needed to make the substance.

Biodegradation: Complete breakdown of an organic chemical compound by microorganisms in the presence of oxygen to carbon dioxide, water, and mineral salts of any other elements present (mineralisation) and new biomass, or in the absence of oxygen to carbon dioxide, methane, mineral salts and new biomass.

Biodegradable: A material is biodegradable if it can, with the help of microorganisms, break down into natural elements (e.g. water, carbon dioxide and biomass).

Compostable: A material is compostable if it undergoes biodegradation by biological processes in home or industrial composting conditions and timeframes, leaving no toxic residues.

Chemical recycling: For the purpose of this report, chemical recycling is described as a form of material recycling where the plastic and/or polymer are modified by a chemical agent or process. Note that, in this report, processes converting plastics to energy or plastics to fuel are not considered chemical recycling.

Depolymerisation: A process that is the reverse of polymerisation, yielding either single monomer molecules or shorter fragments that can be recombined into new polymers. Note that, in this report, only processes that chemically reverse a polymerisation reaction to form molecules that can be directly used to make new polymers are referred to as depolymerisation.

Ecodesign: The integration of environmental aspects into product design with the aim of improving the environmental performance of the product throughout its whole life cycle.

Endocrine disruptor: A chemical or substance that can interfere with endocrine (or hormone) systems at certain doses. These disruptions can cause cancerous tumours, birth defects and other developmental disorders.

Feedstock recycling: Any thermal process that converts polymers into simpler molecules by applying heat to break their covalent bonds. Such processes include pyrolysis, gasification or other thermal cracking. Note that such thermal processes do not dictate what the output is used for. This report recognises them as chemical recycling if the output is used as input for new materials or chemicals, not as fuel.

Mechanical recycling: A form of material recycling where no direct alteration to the structure of the material is made (polymer and any additives in the plastics are retained). Indirect changes can still occur due to mechanical and thermal stress.

Microplastics and nanoplastics: Plastic particles < 5 mm in size. The term is typically used for such particles when found in the environment. Nanoplastics refer to particles < 1 µm in size.

Monomer: A molecule making up the smallest repeating unit in a polymer. Monomers undergo chemical conversion to form the bonds holding them together in a polymer.

Multilayer material: A laminate of different materials forming a material compound, usually a flexible film. Multilayer materials may contain a metal layer or coating, but are often referred to as plastics.

Organic recycling: Defined by the EU Packaging and Packaging Waste Directive 94/62/EC (amended in 2005/20/EC) as the aerobic (composting) or anaerobic (biomethanisation) treatment, under controlled conditions and using microorganisms, of the biodegradable parts of packaging waste, which produces stabilised organic residues or methane.

Polymer: A single molecule of repeating units, which can be linear, circular or branched. Polymers can consist of only one kind of repeating unit (e.g. polyethylene is made from ethylene monomers), or be co-polymers of more than one repeating unit (e.g. poly(ethylene terephthalate) is a copolymer made from terephthalic acid and ethylene glycol).

Plastics: Synthetic or natural organic polymeric materials either of single composition (chemically identical polymers) or formulated (combination of multiple polymers and/or organic or inorganic chemicals).

Solvent-based purification: A process in which the plastic is dissolved in a suitable solvent, in which a series of purification steps are undertaken to separate the polymer from additives and contaminants. The resulting output is the purified polymer, which remains unaltered through the process and can be reformulated into plastics.

Acronyms

ABS	Acrylonitrile Butadiene Styrene
AD	Anaerobic Digestion
AI	Artifical Intelligence
BAT	Best Available Techniques
BEP	Best Environmental Practices
BPA	Bisphenol A
BPS	Bisphenol S
C&I	Commercial & Industrial
CA	Cellulose Acetate
CMR	Carcinogenic, Mutagenic or toxic to Reproduction
DG	Directorate-General
DEHP	Diethylhexyl Phthalate
EEE	Electrical and Electronic Equipment
EPR	Extended Producer Responsibility
EDC	Endocrine Disrupting Chemical
(E)PS	(Expanded) Polystyrene

FCM	Food-Contact Material
FMCG	Fast-Moving Consumer Goods
(G/C)FRP	(Glass/Carbon-)Fibre-Reinforced Plastic
GDPR	General Data Protection Regulation
GWP	Global Warming Potential
ILUC	Indirect Land Use Change
IoT	Internet of Things
IP	Intellectual Property
IRS	Informal Recycling Sector
LCA	Life-Cycle Assessment
MSFD	Marine Strategy Framework Directive
MTOE	Million Tonnes of Oil Equivalent
NIAS	Non-Intentionally Added Substance
PA	Polyamide
PAH	Polyaromatic Hydrocarbon
PBAT	Poly(butyleneadipate co-terephthalate)
PBDE	Polybrominated Diphenyl Ether
PBS	Poly(butylene succinate)
PBT	Persistent, Bioaccumulative and Toxic
PC	Polycarbonate
PCL	Polycaprolactone
PE, HDPE, LDPE	Polyethylene, High-Density Polyethylene, Low-Density Polyethylene
PEF	Polyethylene Furanoate
PET	Poly(ethylene terephthalate)
PHA	Polyhydroxyalkanoates
PLA	Polylactic Acid
PMMA	Poly(methyl methacrylate)
POP	Persistent Organic Pollutant
PP	Polypropylene
PPWD	Packaging and Packaging Waste Directive

PRO	Producer Responsibility Organisation
PTT	Poly(trimethylene terephthalate)
PTTs	Pots, Tubs and Trays
PU(R)	Polyurethane
PVC	Poly(vinyl chloride)
R&I	Research and Innovation
RA	Risk Assessment
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RFID	Radio-Frequency Identification
SME	Small and Medium-sized Enterprise
SVHC	Substances of Very High Concern
TRL	Technology Readiness Level
UV	Ultraviolet
vPvB	Very Persistent and Very Bioaccumulative
VAT	Value Added Tax
WEEE	Waste Electrical and Electronic Equipment
WFD	Waste Framework Directive
WWTP	Wastewater Treatment Plant

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The current plastics system demands fundamental change in which research and innovation, enabled and reinforced by policymaking, play a crucial role. Moving towards a circular economy, we can harness the benefits of plastics, while achieving better economic, environmental and social outcomes. This report aims to inform policy and funding decisions on a circular economy for plastics by providing research and innovation insights from EU-funded projects and the wider scientific community. The report covers the entire plastics value chain, highlighting a broad range of challenges and opportunities. Based on scientific evidence, the insights presented contribute to the transition towards plastic production from renewable feedstock and product design for use, reuse, repair, and mechanical, chemical, or organic recycling. In addition, the report explains how this systemic change can be supported by innovation in business models, collection systems, and sorting and recycling technologies. In this way, plastics could circulate through our society with full transparency at high-value usage, while minimising the risks to human health and the environment.

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