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Science Advisory Council

Packaging plastics in the circular economy

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EASAC

EASAC – the European Academies' Science Advisory Council – is formed by the national science academies of the EU Member States to enable them to collaborate with each other in giving advice to European policy-makers. It thus provides a means for the collective voice of European science to be heard. EASAC was founded in 2001 at the Royal Swedish Academy of Sciences.

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To find out more about EASAC, visit the website – www.easac.eu – or contact the EASAC Secretariat at secretariat@easac.eu

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Foreword

The European Academies' Science Advisory Council (EASAC) was established nearly 20 years ago to provide scientific advice relevant to European policy-making, for the benefit of Europe and its citizens. EASAC's Environment Programme covers all aspects of the environment (terrestrial, freshwater and marine) as well as associated issues such as resource use and productivity. As the issue of the use of plastics in packaging has rocketed up the political agenda, triggered in part by the graphic scenes of marine life affected in television programmes such as The Blue Planet, the European Commission has responded with several measures to encourage the packaging industry to evolve to a more circular framework. Previous EASAC studies have examined issues related to the circular economy, marine sustainability, environmental impacts of bio-crops and other relevant aspects and thus provided a solid foundation for this investigation into the role of packaging plastics in the circular economy.

The current dominantly linear system leads to extensive leakage into the environment by plastics that persist for hundreds or thousands of years. Reforming this brings us into several scientific domains. These include the technical questions of how to recycle different waste streams, behavioural and psychological aspects of the role of consumers, assessing the effectiveness and cost–benefit balance of different regulatory strategies, objectively evaluating the environmental benefits of alternatives to fossil fuel feedstock, how to achieve biodegradability, as well as current and future environmental impacts in terrestrial, freshwater and marine environments. Examining the interactions of these science-based aspects with current and future policies thus required cross-disciplinary expertise which we were able to obtain through the leading world experts nominated by eight of EASAC's member academies. I express our gratitude to the members of our Expert Group for all the time and hard work they spent working with our Programme Director on assembling this comprehensive report.

The pace of regulation is already moving quickly in this field and there are welcome supporting signs from leading companies of their commitment to improving the current situation, and moving to a more circular model for packaging plastics. However, as our report shows, there are some fundamental barriers and potential conflicts of interest in the long and complex value chain, which starts with fossil fuels and ends with plastic in the environment. It is not a problem that individual stakeholders can solve on their own, and the motives and actions of individual stakeholders are not currently aligned with the overall objective of a more circular use for packaging plastics. In this report we examine the issues from a systems perspective and highlight these potential conflicts so that they can be better understood and addressed.

Our Expert Group, supported by EASAC's member academies, has made several important recommendations where the underlying theme of a greater sense of responsibility provides a common thread. It is questionable whether producers of plastic raw materials can continue to see their business model as based on 'business as usual' with annual growth rates of several per cent; it should help if packaging manufacturers can simplify their current complex mixtures to become easier to recycle; retailers can contribute by thinking as hard about effective end-of-life reuse or recycling as they do about the attractiveness of their packaging to the consumer; consumers who have embraced the 'on the go' and 'throwaway' culture which has led to so much littering could start to see packaging as something on loan rather than to be discarded in the simplest way possible. Finally, the recycling industry will need upgrading and expansion if we are to stop the unethical and environmentally damaging export of waste we cannot handle in Europe to countries lacking the facilities to properly recycle and dispose of it once it has arrived.

Taking such a systems approach across the current, predominantly linear, value chain may encourage the already extensive and well-developed measures within the European Union's regulatory system and within leading companies to aim higher, to ensure that the many benefits of plastics can be realised without having to accept the adverse effects resulting from their widespread contamination of our environments.

Professor Christina Moberg
EASAC President

Summary

Plastics are an essential material for products in almost all sectors of the economy, and the single word 'plastics' cannot convey their vast complexity as a result of the range of monomers available, the ability to control their molecular structure and the wide range of additives and fillers which together make thousands of different 'plastics'. In terms of **plastics for packaging**, they can offer an almost infinite range of options for manufacturers in terms of function (durability, preserving hygiene and quality, etc.) as well in designing shape, colours or labels to convey marketing messages. However, the durability and resistance to degradation of plastics means that if they 'leak' into the environment, they persist. Quantities in the environment have been increasing rapidly and their impacts, especially on the marine environment, have attracted public and political attention. Currently, the amount of plastics entering the environment exceeds the amount that is recycled, with large quantities entering via rivers from the Asian and African continents.

Reducing leakage to the environment and improving recycling rates for packaging plastics are objectives of the European Commission's circular economy package, its plastics strategy and specific measures on the use of 'single-use plastics' (SUPs). To assist in the development of these policies, the European Academies' Science Advisory Council (EASAC) decided in November 2018 to establish an Expert Group to look at scientific aspects of plastics packaging and the circular economy.

This report is the result of an 18-month investigation and has been endorsed by all of EASAC's member academies. We review the negative consequences of the current linear economy for plastic packaging, the scope for improvement towards a more circular pattern of production and use, and options for increasing recycling rates and reducing leakage into the environment. The scientific issues examined relate to the environmental impact of plastics in the environment, extended producer responsibility, technical issues in recycling, consumer behaviour, the role of bio-based and degradable plastics, and targets for research and innovation. The implications for policy are presented in Chapter 8 of the report and summarised here.

Plastics and the linear economy

The current packaging plastics value chain is an example of the 'linear economy'. Fossil fuel feedstock (oil and gas) produces monomers, which are polymerised to the basic plastic resin. These can be compounded, often with a range of chemical additives, into plastic materials with the many different properties, colours, shapes, etc. required for final use. After the consumer has finished with the packaging (often after only one use), it is discarded, from where only a proportion is currently recycled with most going for incineration or landfill, or leaking into the environment.

This is a fundamentally flawed model incompatible with a wide range of policy objectives including:

- Environmental. Owing to the lack of any significant capacity in the environment to degrade or otherwise remove plastic particles, they can now be found in all parts of the global environment, while being ingested by living organisms — including ourselves.
- Circular economy. This has the objective of reducing material consumption and material flows. In contrast, the linear nature of the current value chain and low recycling rates are predicated on continued rapid growth in production and consumption.
- The United Nations Sustainable Development Goals. The current linear model is incompatible with Goals 11 (sustainable cities and communities), 12 (responsible production and consumption), 13 (climate action), 14 (life below water) and 15 (terrestrial ecosystems).
- Existing legislation. The Waste and Marine Strategy Framework Directives, and international marine pollution conventions, are compromised by the low recycling rates and high rates of leakage.
- Ethical issues. Plastics waste from the European Union (EU) and other high-income countries worldwide have been exported in large quantities to middle- and low-income countries. However, crude recycling methods, inadequate disposal or abandonment have adverse effects on the environment and public health. Moreover, leakage from such practices can clog waterways, causing flooding and adding to the plastics entering the marine environment.

This report identifies issues arising from such systemic failures in the linear economy model for plastics. These are summarised in the Table, together with the location in the report where these issues are addressed.

System failures and summary of policy options in this report

<table>
<tr><th>Stage in the value chain</th><th>System failure</th><th>Policy options</th><th>Report section</th></tr>
<tr><td>Fossil fuel feedstocks for monomer</td><td>Social and environmental costs are not internalised into prices.</td><td>Charging full costs for carbon dioxide, methane and other greenhouse gas emissions, and other costs currently borne by society.</td><td>8.6</td></tr>
<tr><td>Bio-based feedstocks</td><td>Potential conflicts with food, biodiversity, direct and indirect land use change, etc.</td><td>‘Bio’ does not equate to environmentally benign. Full life cycle assessment required.</td><td>6.1</td></tr>
<tr><td rowspan="6">Plastics manufacture</td><td rowspan="3">Driven by continued high growth rate linear model. Does not bear the social and environmental costs.</td><td>Regulatory requirements for end-of-life and recycling plans integrated into value chains and product design and engineering.</td><td>8.4</td></tr>
<tr><td>Plastic tax or mandating percentage of recycled content.</td><td>8.6</td></tr>
<tr><td>Prevention as part of ‘Plastics in the circular economy’ package.</td><td>8.2</td></tr>
<tr><td>Substitution possibilities by other packaging materials likely to be limited.</td><td>Full life cycle assessment required with comparative assessments between alternatives.</td><td>8.3</td></tr>
<tr><td rowspan="2">New resins offering biodegradability are not offering a solution to environmental leakage while interfering with recycling.</td><td>Restrict compostable plastics to compostable contents.</td><td>6.3</td></tr>
<tr><td>Realistic tests for biodegradability before their introduction.</td><td></td></tr>
<tr><td rowspan="2">Packaged goods manufacture</td><td rowspan="2">Inadequate attention to end-of-life issues in the selection of resin, additives and packaging format.</td><td>Full costs extended producer responsibility with eco-modulation. Regulatory requirements for end-of-life and recycling planning.</td><td>3, 8.4</td></tr>
<tr><td>Simplify resins and formats.</td><td>8.6</td></tr>
<tr><td rowspan="2">Retailing</td><td rowspan="2">Inadequate attention to end-of-life issues in the choice of goods and provision of recycling options.</td><td>Deposit–return schemes for beverage containers, extending to other containers.</td><td>5.3, 8.5</td></tr>
<tr><td>Retailers accept responsibility for collection and effective recycling of containers after use.</td><td>8.8</td></tr>
<tr><td rowspan="4">Consumers</td><td rowspan="2">Single-use/throwaway culture.</td><td>Measures to reduce demand for bottles (e.g. water fountains, encouraging reusable containers).</td><td>5.3, 8.5</td></tr>
<tr><td>Encourage seeing packaging as ‘on loan’ to be returned for reuse or recycling.</td><td>5.3</td></tr>
<tr><td>Insufficient incentives and information to encourage recycling and to reduce usage.</td><td>Deposit–return schemes for containers. Consumer awareness, provision of disposal options to prevent littering.</td><td>5, 8.5</td></tr>
<tr><td>Poor labelling.</td><td>Labelling related to local recyclability.</td><td>8.7</td></tr>
<tr><td rowspan="5">End-of-life processing</td><td rowspan="3">Continued heavy reliance on exports, landfill and incineration.</td><td>Support for a ban on exports to outside EU.</td><td>8.1</td></tr>
<tr><td>EU and international aid agencies to developing countries to improve waste management infrastructure and prevent dumping of plastic waste into the environment.</td><td>8.10</td></tr>
<tr><td>Ban on landfill brought forward.</td><td>8.1</td></tr>
<tr><td rowspan="2">Low-value mixed plastic waste recycling uneconomic.</td><td>Apply a recycling hierarchy preferring closed loop, followed by material recycling, molecular recycling and finally energy recovery.</td><td>4, 8.6</td></tr>
<tr><td>Develop and apply concept of advanced plastic reprocessing facility.</td><td>4.2</td></tr>
</table>

Key stakeholders

Plastics pollution is a systemic problem, from extraction and raw plastic production, to production of goods, transport, consumption, waste collection, management, recycling and disposal. Reforming the system requires the engagement of many stakeholders whose role influences the amount and fate of plastic packaging, such as the following.

- **Plastic resin manufacturers, packaging materials manufacturers and packaged goods manufacturers** decide the materials and formats which are presented to the consumer. End-of-life considerations may be lacking or, on the other hand, influenced by considerations of reputation and corporate social responsibility.

- **Retailers, especially food retailers** decide the extent and nature of packaging used at point of sale and whether to continue to rely on single-use packaging, or offer low-plastic options for products and services, and collection and recycle infrastructure.

- **Consumers** lack information about production, chemicals usage, or clear information allowing for comparison between products; they are thus limited in the role they can play in reducing plastic use and pollution. Nevertheless, consumers can play an important role in some cases: for instance whether to purchase a plastic product, whether to reuse (e.g. bottles or bags), and in avoiding littering.

- **Citizens, environmental organisations** and **scientists** may collaborate on citizen science projects, beach clean-ups or social media campaigns.

- **Educational systems and educators** can offer curriculum material and innovative educational solutions, aiming to improve the pro-environmental behaviour of the younger generation.

Regulatory strategies will be more effective where the interests and motivations of different actors are aligned, and may have to address conflicts: for instance the conflict between the continued investment predicated on continued high growth rates of the linear economy, and societal and environmental objectives such as limiting climate change, reducing plastic in the environment and improving resource efficiency.

Key messages in this report include the following.

Exports of plastic waste for 'recycling'

EASAC recommends that the Commission should support an effective ban on exports of plastic waste to countries outside the EU, independently of recent amendments to the Basel Convention. Most of the EU's plastic waste collected for so-called 'recycle' has been exported and much has gone to countries where inadequate waste management and recycling infrastructure has already led to leakage into the local environment and ultimately the oceans. This is incompatible with the objectives of sustainable development and the precautionary principle and, since environmental pollution does not recognise international boundaries, increased leakage elsewhere in the world will ultimately also affect the EU's marine environment. Ethical objections also exist to a practice where high-income countries are exporting waste to low- or middle-income countries without consideration of the subsequent impacts on the receiving country's environment or public health.

Landfill

The loss of the low-cost option of export should not divert plastic waste to landfill, and a **target of zero plastic waste to landfill** should also be adopted at an early date, consistent with encouraging the development of a circular economy for plastics in the EU.

Packaging plastics and the circular economy

More emphasis is needed in policy-making to reduce the amount of plastics, although replacement of plastic by alternative materials is in most cases not justified on resource or environmental grounds. The emphasis should be on reducing unnecessary use (when technically feasible) and for plastic products to be designed to allow for reuse in order to minimise the amount of waste generated. This is because a key aim of the circular economy is to reduce material flows and increase the length of time in which resources are used- regardless of the type of material. **EASAC thus recommends that a reduction in material flow should be an explicit objective of the 'Plastics in the circular economy' package**. The priorities should be in the order of the '6Rs': reduce (raw material use); redesign (design products for reuse or recycling); remove (SUPs when practical); reuse (returnable uses or refurbishment); recycle (preferably closed-loop recycling whereby waste material is used in the manufacture of the same product); recover (extract chemicals or fuels, or incineration for energy production).

Extended producer responsibility (EPR)

Differentiated fees applying to *all* packaging combined with eco-modulation which rewards easily recyclable packaging and penalises difficult-to-recycle materials can generate substantial environmental benefits. EPR is the primary tool envisaged for incentivising manufacturer and retailer choices towards more efficient end-of-life recycling. However, current EPR fees appear insufficient in many Member States to influence manufacturer and retailer priorities. Estimates of the cost of losses to natural capital from plastic packaging (greenhouse gas emissions, air, water, land pollution from inadequate waste management and littering) support EPR fees at or above the highest existing Member States' charges (€250 on average per tonne of packaging material), with steep eco-modulation (for example in Italy, fees for the most readily recycled are €150 per tonne, while those for unrecyclable materials are €546 per tonne). The EPR system should include imported goods and packaging in products purchased via the Internet, especially since these tend to use more packaging than goods bought in a store.

Deposit–return schemes (DRS)

Successful experiences in several Member States supports the wider deployment of DRS. Enhanced curbside collections currently preferred in some Member States are unlikely to achieve the very high return rates achievable through DRS, and will be less effective in reducing littering. Moreover, increased supplies are already required to fully use existing polyethylene terephthalate (PET) recycling capacity, and demand is expected to grow as beverage manufacturers increase their commitment to using recycled content. On the other hand, the net environmental balance for **refillable containers** is highly case-specific and there is scope for additional research and guidance on assessing the benefits and implementation of potential schemes.

Consumer behaviour

Consumer behavioural research shows that consumers are most influenced by prices, not only because of the financial incentives associated with them, but also because they help signify a new social norm. The experience of plastic bag charges shows that even small charges can be effective. **EASAC recommends that consideration should be given to extending DRS to a wider range of containers and single-use beverage bottles (e.g. high-density polyethylene (HDPE) containers, coffee cups)**, on the basis of the principle that such containers should be seen as 'on loan'. Pro-social and environmental attitudes can be encouraged by a comprehensive approach to public information and awareness and on adjusting social norms with the help of a sustained media presence.

Priorities in recycling

EASAC has examined technical obstacles to more recycling. While some recycle streams are economic (particularly the clean recycling streams from separate collection of PET bottles in a DRS scheme), the value of mixed packaging plastics is so low that economic recycling within the EU has been difficult, leading to the large proportions exported, incinerated or landfilled. If, as previously recommended, export from the EU and landfill are to be stopped, it is essential to develop integrated recycling systems which can deal with all waste plastics, while achieving net savings in emissions and resource use. **EASAC considers that such advanced plastics recycling/reprocessing facilities should follow this hierarchy:**

- The first priority is to recycle to use in the same product: **closed-loop recycling** typified by recycling PET bottles to PET bottles.
- The second is to recycle for use in another product (open-loop recycling); especially where quality cannot be maintained, this will be for lower-quality uses: **downcycling**.
- Third would be extracting valuable chemicals or fuels through chemical treatment or pyrolysis: **molecule recycling**.
- Finally, where the above are not feasible, incineration can extract energy from the remaining plastic waste: **energy recovery**.

Improving the viability of recycling

The technical and economic viability of recycling would be improved by simplifying the number of polymers that can be used for specific applications. In particular, the wide range of additives which may be used in different forms of packaging (section 2.2) limits recycling possibilities. Limiting the main polymers used in large volume applications to transparent PET (which is generally devoid of additives) and polyethylene (PE) (which generally includes just antioxidants) would improve recyclability. Recent technological advances allow even the multilayer packaging comprising different materials to be replaced by multilayer packaging using the same resin so that it can be recycled. Companies engaged in the Global and National Plastic Pacts are already improving the recyclability of the plastics used, but they comprise only a minority of packaging producers and users. While it is hoped that a robust EPR system will encourage trends towards uniform recyclability, **the European Commission should monitor progress and consider further regulations if the leading companies' examples are not followed by most users of packaging plastics.**

Competition with prices of virgin plastics

A fundamental barrier to greater demand for recycled materials is competition with virgin raw materials. **Virgin plastics prices** continue to be low because oil and gas prices do not reflect social and environmental costs; on the contrary, fossil fuels continue to receive subsidies from many governments inside and outside the EU. This is a fundamental barrier to improving rates of usage of recycled material and underpins measures under discussion in some Member States either to introduce a plastics tax or to require minimum recycled contents. With a budget contribution based on unrecycled plastic packaging currently under consideration by the European Commission, Member States can consider recovering this via a plastics tax, for example to generate income to support additional capacity and diversity of recycling resources. **However, further examination is warranted on how any such tax would interact with an enhanced EPR system, whether it could lead to perverse incentives to switch from plastic packaging to materials with greater environmental impacts, and issues of monitoring, enforcement and other factors.**

Labelling

A uniform and mandatory labelling related to actual (rather than theoretical) recyclability would be beneficial. Currently, labelling differs between Member States, is voluntary and its relevance depends on local recycling capacity. Consumers require information that is simple, reliable and trustworthy; the current diverse and generic system fails to meet these criteria.

Single-use plastics (SUPs)

Much SUP littering is associated with 'on the go' consumption of food and beverages and reliance on basic refuse collection services to avoid it. Integrating recycle loops into the many dispersed outlets (e.g. for coffee cups, or fast-food trays and wrappers) is a major challenge but **EASAC considers retailers should have a duty to provide on-site collection points** for the packaging of the food and beverages they sell, and ensure these are effectively recycled. The experience of the plastic bag charge, which showed that even small charges can be extremely effective, suggests that deposit systems should be extended to a broader group of containers to encourage consumers to see packaging as being 'on loan' and therefore returnable to be efficiently reprocessed.

Environmental pollution

Plastic's leakage is responsible for massive mortalities and injuries to marine life. Marine litter is already covered under the Marine Strategy Directive and international conventions. Although the EU is addressing major sources of leakage into EU waters via initiatives on fishing and other sources of marine litter, **the EU should also encourage redirection of international aid from the World Bank and other international aid agencies from supporting fossil fuel infrastructure to improving waste management infrastructure in countries with high leakage.**

Impacts on terrestrial and freshwater systems are poorly characterised and understood, and require further research and monitoring.

Macroplastics and microplastics

Many studies have demonstrated the adverse effects of macroplastics especially on marine life, but it is still unclear how far small plastic particles (microplastics) have different effects than naturally occurring sediments or organic particles of similar size in the seas, or in soils. In view of the established adverse effects of macroplastics and their importance as a source of microplastics, **it is appropriate to continue to focus regulatory actions on macroplastics**. Nevertheless, the extent to which microplastics are contaminating the environment – from the deep ocean to the Polar seas, from drinking water to seafood – raises issues that are not readily addressed by standard evidence-based risk analysis. A critical policy issue is the extent to which the precautionary principle should be applied. **EASAC recommends that a debate within society be triggered to determine the degree to which this is applied and that, in the meantime, deliberate addition of microplastics by companies to products that will enter the environment should be avoided.**

Bio-based plastics

The term 'bio' does not equate to reduced environmental impact since alternative feedstocks to fossil fuels can be associated with high greenhouse gas emissions, competition with land for food, or driving land use change. To avoid misleading consumers, companies should quantify any environmental benefits claimed. While there are applications where bio-based plastics may be excellent, such evaluations should be based on life cycle assessments (LCAs) and not on simplistic assumptions or claims that 'bio' signifies lower environmental impact. Further improvement in the LCA methodology should be researched.

Biodegradability and compostability

Plastics with a degree of biodegradability have been developed but their potential is limited at present. The ideal target of a plastic that breaks down naturally in the environment remains elusive since most applications of plastics require durability, and it is a basic premise that a material which can degrade in the environment should not degrade during its shelf life. There are thus only a limited number of products that can meet biodegradation tests in the marine environment and even these maintain their integrity for months, during which time the risks of entanglement and ingestion remain. **EASAC encourages further research to develop plastics that degrade more swiftly through natural processes**, but faster and more reproducible rates of degradability are needed to offer a solution to the problem of often-littered SUPs. At the present state of technology, composting also offers most benefit when the plastic is contaminated by a substance that is also disposed of by composting: for example, compostable bags used in the closed loops of food waste recycle.

Final comment

In the same month (March 2020) as the publication of this report, a new European Plastics Pact was announced which shares many of the basic principles and essential objectives identified here. This is further evidence that the leaders in the industry (from the global leaders active with the World Economic Forum and Ellen MacArthur Foundation in the Global Plastics Pact, through regional associations such as Plastics Europe to leaders of national plastic pacts) accept that the linear economy for plastics must change towards a circular model. However, as pointed out in this analysis, there are many technical barriers and potential conflicts of interest that must be resolved to reduce leakage into the environment and make better use of resources. Governments, businesses, local authorities, consumers and non-governmental organisations need to work together to overcome these, and create an environment for plastics use in packaging which allows the many benefits of plastics to be exploited without the current extensive negative side-effects. Whether it is the role of regulation, changes in the attitudes of consumers, designing and marketing packaging, or upgrading the recovery and recycling at end-of-life, it is hoped that the analyses of key science and technology-related aspects in this report will assist all stakeholders in their efforts to accelerate moves towards a circular economy for plastics packaging.

1 Introduction

Plastics (a generic term used in the case of polymeric materials that may contain other substances to improve performance and/or reduce costs (IUPAC, 2019)) have undergone multiple changes in composition and innovations in manufacturing since they entered widespread use in the 1950s. There are now many basic polymer resins that can be modified and refined to provide a wide range of plastics with properties adjusted to the needs of a huge range of applications. Plastics can be flexible or hard, melt or set with temperature, be easily set or milled into any shape, be any colour, transparent or opaque. Fillers, plasticisers and additives allow the delivery of a wide range of desirable properties (including strength, durability, light weight, thermal and electrical insulation, barrier capabilities, flame retardant, antimicrobial, ultraviolet-resistance, etc.)- all at a competitive cost/performance ratio and combination of properties that are difficult to achieve with alternative materials. Plastics have consequently become an essential material for products and sub-assemblies in almost all sectors of the economy. The single term 'plastics' hides the vast complexity of the materials produced—not only are there many different chemical starting materials (monomers), but the degree of polymerisation can be finely adjusted to make many different variants on the resulting plastic material. When the wide range of additives and fillers are included, this offers an almost infinite range of options for manufacturers to choose from when designing shape, colours or labels to convey marketing messages to the consumer.

These advantages do, however, come with costs (externalities) which have not been addressed in the linear economy of 'take-make-use-dispose' (EC, 2015). The durability and long life of plastics, which are beneficial characteristics during use, become disadvantages when they 'leak' into terrestrial, freshwater and marine environments, since their breakdown is slow or lacking, with most remaining in some form in the environment. In recent years, the environmental impact, especially on the marine environment, has become increasingly well documented and attracted public and political attention. Effects can be seen on marine life from the macro scale (fishing nets, plastic ropes, plastic bags, etc.) and medium scale (e.g. bottle fragments, cigarette lighters, toys, toothbrushes, etc.). Microplastics (small fragments below 5 mm size) and nanoplastics (below 0.1 mm) are now detectable in almost all aquatic media (see, for example, Meng *et al.*, 2019) which includes bottled water and beer (Eerkes-Medrano *et al.*, 2018; Kosuth *et al.*, 2018; Mason *et al.*, 2018; Koelmans *et al.* 2019), in snow (Bergmann *et al.*, 2019), on mountains (Zhang *et al.*, 2019) and in the atmosphere of cities (Wright *et al.*, 2019) where they can be inhaled (Gasperi *et al.*, 2018). Such negative externalities are not accounted for in the price of plastic products; nor do prices yet reflect the costs of disposal or contribute sufficiently to an efficient recycling system. Such costs are borne by society and the environment and have until recently remained 'out of sight' to the consumer. Moreover, several of the United Nations Sustainable Development Goals are compromised by the current linear model of the plastics economy, with Goals 11 (sustainable cities and communities), 12 (responsible production and consumption), 13 (climate action), 14 (life below water) and 15 (terrestrial ecosystems) particularly relevant[1].

Reducing leakage to the environment and improving recycling rates are particular challenges for packaging plastics whose variety and low value lead to low recycling rates. Moreover, plastic packaging comprises a substantial part of litter and persists in the environment, in contrast to other materials which are either not littered to the same extent (glass, metal) or decompose (paper). Reflecting the special challenges of packaging plastics, the European Commission included them as a priority for action within its circular economy package (EC, 2015), and has since followed this with a plastics strategy (EC, 2018a), specific proposals on the use of 'single-use plastics' (SUP) (EC, 2018b) and a subsequent directive (EC, 2019). The Ellen MacArthur Foundation (EMF) also launched its initiative for a 'New Plastics Economy' in 2016 and is promoting this through its Global Plastics Pact (EMF, 2016, 2017, 2019).

EASAC has already provided input to the debate on the circular economy within Europe through its statement in 2015 (EASAC, 2015) and its reports on indicators and critical materials (EASAC, 2017a, 2017b). EASAC thus considered whether there were aspects where Europe's science academies could contribute to the current EU policy debate. After discussions in the Environment Steering Panel, EASAC Council decided in November 2018 to establish an Expert Group (Annex 1) to look at scientific aspects of introducing more circularity into the value chain (from design to end-of-life, reuse and recycling) of packaging plastics. The Expert Group has reviewed the many documents available from

[1] https://www.un.org/sustainabledevelopment/sustainable-development-goals

previous studies and the open literature, has identified several critical issues where science and technology interact with policy, and presents in the final section its own conclusions and recommendations about the direction of future policy on packaging plastics and their environmental impact. It is intended that this report should assist in developing effective policy actions in the EU, and be helpful to the debate globally on the measures needed to reduce the environmental impact of packaging plastics.

2 Background

2.1 Global and European dimensions

Global production of plastics has increased 20-fold since the 1960s, reaching 359 million tonnes per annum in 2018 of which 62 million tonnes were in Europe (Plastics Europe, 2019). The plastics industry is an important part of the European economy, with a turnover of €360 billion in 2018. This rapid growth has been driven by two underlying trends. One is the continued growth in population and consumer demand exhibited in all markets, so that current levels of consumption exceed the capacity of the planet to provide sustainably, threatening the quality of life for future generations (the antithesis of sustainable development)[2]. The second is the replacement of other materials (e.g. paper, metals, glass) because of the superior cost:performance ratio of plastics, and by the addition of new applications (e.g. by adding plastic packaging to previously unwrapped goods, replacing reusable items by disposable items). The Expert Group has focused on the use, end-of-life and recycling of plastics packaging rather than the broader sustainability of the growth in human demand for resources. However, this broader picture needs to be kept in mind when we consider the *need* for plastics and the potential for replacing with other resources, since continued unlimited growth in demand for *any* kind of material will inevitably exacerbate the serious environmental problems given the limited, finite nature of our Earth. This is particularly relevant given the steady increase in the proportion of oil and gas demand which is driven by plastics (IEA, 2018).

Cumulatively and globally, it is estimated that 6.3 billion tonnes of the 8.3 billion tonnes of plastic produced up to 2016 has ended up as waste, of which only 9% is recycled (Geyer *et al.*, 2017). Plastic waste collected in Europe was 29.1 million tonnes in 2018 (Plastics Europe, 2019), of which 17.8 million tonnes were plastic packaging waste. Bottles are one of the most common types of plastic packaging waste (480 billion plastic bottles were sold globally in 2016) and comprise an important recycle stream in the EU. Overall, however, the European Commission notes (EC, 2018a) that only approximately 30% of plastic waste collected is destined for recycling, and most goes either to landfill or to incineration (31% and 39% respectively). The quantity of plastics re-entering the value chain as raw material accounts for only around 6% of plastics demand in Europe; moreover, profitability in the plastics recycling sector is low, holding back investments in new recycling capacity. Resolving these fundamental structural problems is thus a primary challenge for European policy.

Limits to recycling capacity within the EU have led to a dependence on export to other countries with little or no consideration of the fate of the waste in the receiving country[3]. Since China ceased to accept import of mixed plastics waste in 2017, export shifted to other countries such as Malaysia, Vietnam and Thailand despite the limited recycling facilities in such countries. As described in Chapter 8, such imports are successively leading to further restrictions on imports and, despite exporters diverting to further countries such as Indonesia and Turkey, there has been an overall reduction in global shipments of plastic waste. Public awareness of the environmental impacts of these practices is adding to pressure for EU countries to tackle plastic waste within Europe.

In recent years, the public has also become increasingly aware of the environmental impacts of plastics through accidental or deliberate release to terrestrial, aquatic or open drainage systems. Some plastics released into the terrestrial environment may remain there (for instance agricultural plastics entering the soil), but large quantities enter rivers (either directly through runoff or after passing sewage treatment systems) and ultimately enter the sea and join plastic waste released directly (e.g. from beaches or vessels). Estimates (Jambeck *et al.*, 2015) suggest that between 5 million and 13 million tonnes (1.5% to 4% of global plastics production) enter the oceans each year, most from Asia and Africa. Some is stranded on beaches, some fragment into smaller particles and remain in the water column, heavier particles may sink to the seabed (especially some fishing gear), but much is transported by marine currents to locations far from the point of origin. Plastics are thus found in remote areas such as the Arctic and the ocean

[2] There are many indicators of the unsustainability of current population and consumption trends. For example the consumption of resources now exceeds the quantity that can be provided sustainably by 60% (https://www.footprintnetwork.org/); land available to support human population growth and food has replaced over 75% of the Earth's land area and led to huge loss in biodiversity, land degradation and climate change (IPBES, 2019); planetary boundaries that are considered to be critical to the maintenance of conditions that have allowed human civilisation to develop to its current state are being approached or in some cases, exceeded (Steffen *et al.*, 2015, 2018).

[3] Plastics Europe (2018) report 63% of the packaging waste recorded as 'recycled' in 2016 was exported outside the EU, but decreased by 39% to 2018 (Plastics Europe, 2019). In the UK (RECOUP, 2018), 1,044,363 tonnes of plastic packaging were declared as recycled in 2017 of which 66% was exported. Germany is the third largest exporter of waste after the USA and Japan, sending 114,000 tons of plastic waste just to Malaysia from January and October 2018 (Böll/BUND, 2019).

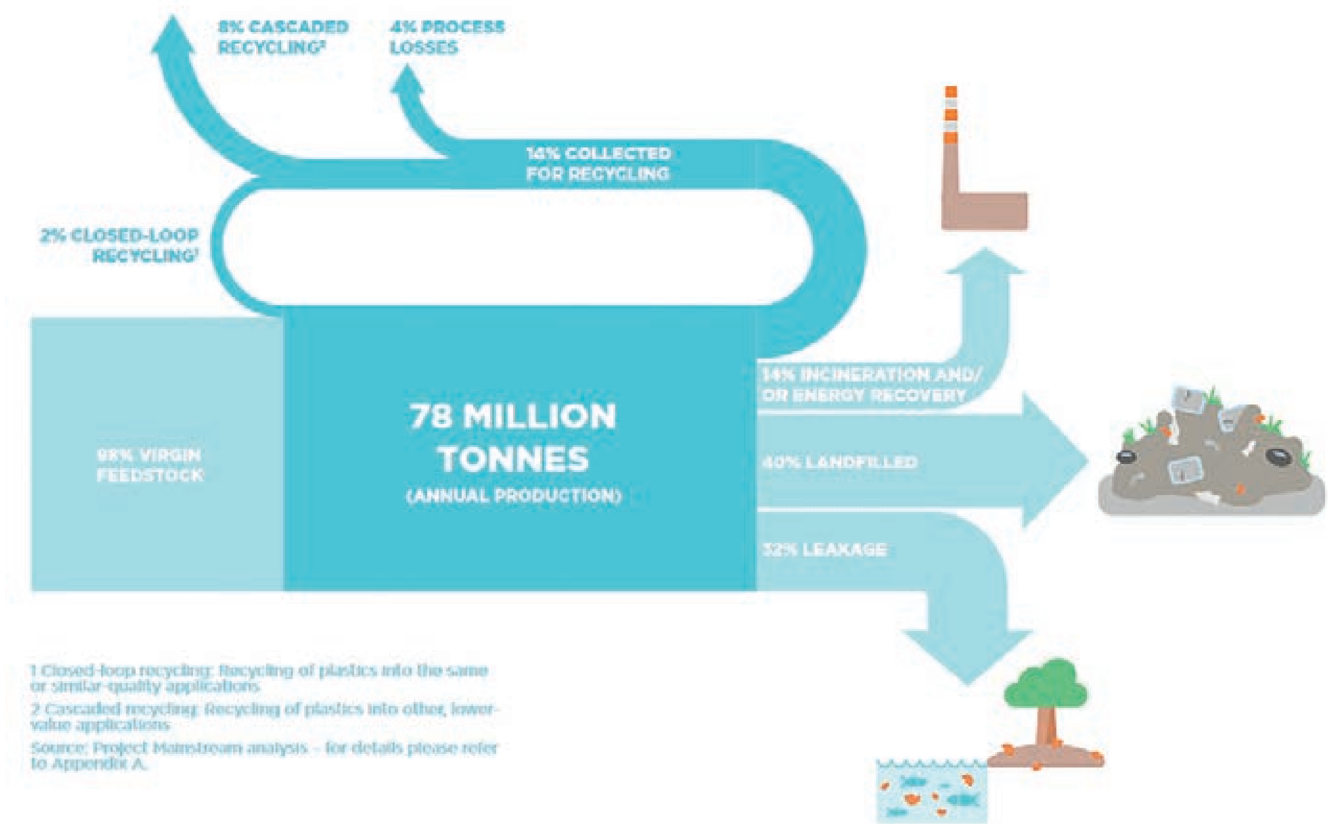


Figure 1 Material flows for global plastic packaging materials in 2013 (EMF, 2016).

deeps[4], and get trapped in ocean gyres. Negative environmental effects on tourism, fishing and marine life increase with the increasing amounts of plastic wastes in the environment, and the United Nations Environment Programme (UNEP, 2016) estimated that the economic value of such damage is at least US$8 billion per year globally. The external effects of plastic leakage thus have a large international component and any solution requires collaboration between countries (Borrelle *et al.*, 2017).

An earlier material flow analysis for packaging plastics globally by (EMF (2016), illustrates clearly how the system is characterised by a dominant linear flow with low recycle rates and high leakage. From the perspective of sustainable development and the circular economy, the current system offers many opportunities for improvement to reduce negative impacts on the environment and improve the efficiency with which the resources and energy embedded in plastics are recovered. In this context, the EMF has launched a global initiative to mobilise large companies to work towards a 'New Plastics Economy' redesigned along circular economy principles (Box 1). UNEP has similar aims, and the World Economic Forum and many international companies have indicated their support.

2.2 Plastics: some complexities

Reforming the plastics value chain towards a more circular model needs to take into account several complexities. Examples of these are discussed below.

2.2.1 The plastic packaging value (supply) chain and stakeholders

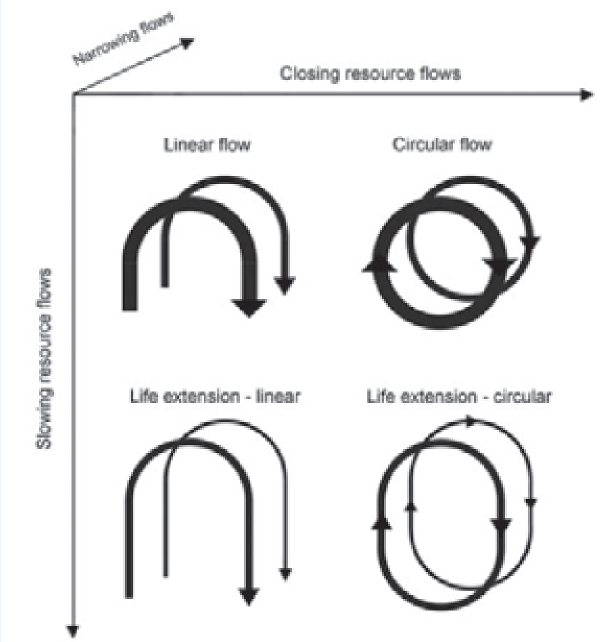
Manufacturing and applying packaging involve many stakeholders and a long value chain. The starting point has historically been the petrochemical refinery where crude oil is refined to produce the hydrocarbons that can be used as the monomers for producing different polymers (ethylene to polyethylene, propylene to polypropylene, etc.) in a polymerisation reactor using

[4] Woodall *et al.* (2014) found that microplastic was up to four orders of magnitude more abundant in deep-sea sediments from the Atlantic Ocean, Mediterranean Sea and Indian Ocean than in contaminated sea surface waters. Peng *et al.* (2018) found that microplastic abundances in hadal sediments of the Mariana Trench ranged from 200 to 2200 pieces per litre, higher than those in most deep-sea sediments. Cozar *et al.* (2017) showed that the Arctic Ocean contains microplastics originating particularly from northwestern Europe.

Box 1 Basic objectives of the circular economy

As described in EC (2015), the circular economy aims to reduce the demands on nature's resources to within sustainable levels. The primary mechanisms are through reforming resource flows in the following three areas (Bocken *et al.*, 2016).

A. **Narrowing** the flow of resources by increasing resource use efficiency (use less resource for each product, or avoiding the need for use at all).
B. **Slowing** resource flows (make the resource stay in use longer).
C. **Closing** the resource loop (ensure the resources are recycled and used in production again).



The role of each of these methods in shifting from the linear to circular economy can be shown in a three-dimensional sketch as in the figure (Bocken *et al.*, 2016). The various ways in which these three principles can be applied to plastics have been summarised by Ten Brink *et al.* (2016) in their review of the circular economy tools that are relevant to any strategy for reducing the impacts of plastics on the environment.

catalysts. Each basic polymer (or resin) has its own properties, molecular structure and size depending on the various types of basic monomer used. The raw resin then has to be **compounded**, which is the process of adding additional materials into a molten plastic base to produce a material with the qualities desired in the application. Additives and modifiers may result in plastic with a particular colour, texture, strength, etc. Once the additives have been blended into the base material and a homogeneous product obtained, the material is cooled and extruded into pellets. Any recycled material will be incorporated at the compounding stage.

These raw plastic materials are then used at the next stage which is the conversion of the pellets to the packaging format — films, bottles, containers, etc. The basic function of the packaging will be to protect or enclose products destined for storage, shipping and sale. Packaging also takes in the product manufacturer's marketing efforts, and, for many manufacturers, the way they package their products signifies their brand, and is thus a critical part of their business model. The design of the package for a product can either take place within the product manufacturer or through specialist companies that work with the manufacturer to design the desired package. The packaged product then enters the distribution system from the product manufacturer to the retailer, the consumer and ultimately post-consumer disposal.

Shifting to a more circular use pattern requires that change be effected along this value chain (Figure 2), which proceeds along several stages (each involving many possible types of plastic material and combinations of materials and additives) with increasingly large numbers of stakeholders, culminating in the billions of consumers who are responsible for decisions on final disposal after use. Rethinking and improving the functioning of such a complex value chain requires efforts and cooperation by all stakeholders: plastics producers and converters, product manufacturers, retailers, consumers, waste handling and collection operators, recyclers and users of recyclates within the legal and regulatory framework provided by governments.

This chain offers several points at which regulatory interventions can be considered, or boundaries which may dilute or block feedback between end-of-life treatment and earlier stages. Although there are no stakeholders directly interested in plastic pollution, contemporaneous motives of stakeholders may not be aligned: for example, primary feedstock producers are motivated to *expand* production, in contrast to the objective of circularity to *reduce* material flows. Given the regulatory focus on post-consumer packaging, it is important to note that plastics will leak from every step of the value chain — in production, transportation[5] and use as well as disposal post-consumption. Focusing on the consumer with their limited ability to 'solve' problems with plastics pollution should not detract from the need to consider the system changes necessary to solve the problems of plastic pollution and its causes.

2.2.2 The materials

As noted in the introduction, 'plastics' is a generic term applied to several primary polymers (resins), the

[5] For example, Karlsson *et al.* (2019) find the loss of plastic pellets/nurdles is still a significant source of leakage from plastic production sites and from spills by companies involved in transport, storage, cleaning and waste management, requiring increased responsibility and accountability to reduce such spills and leakage.

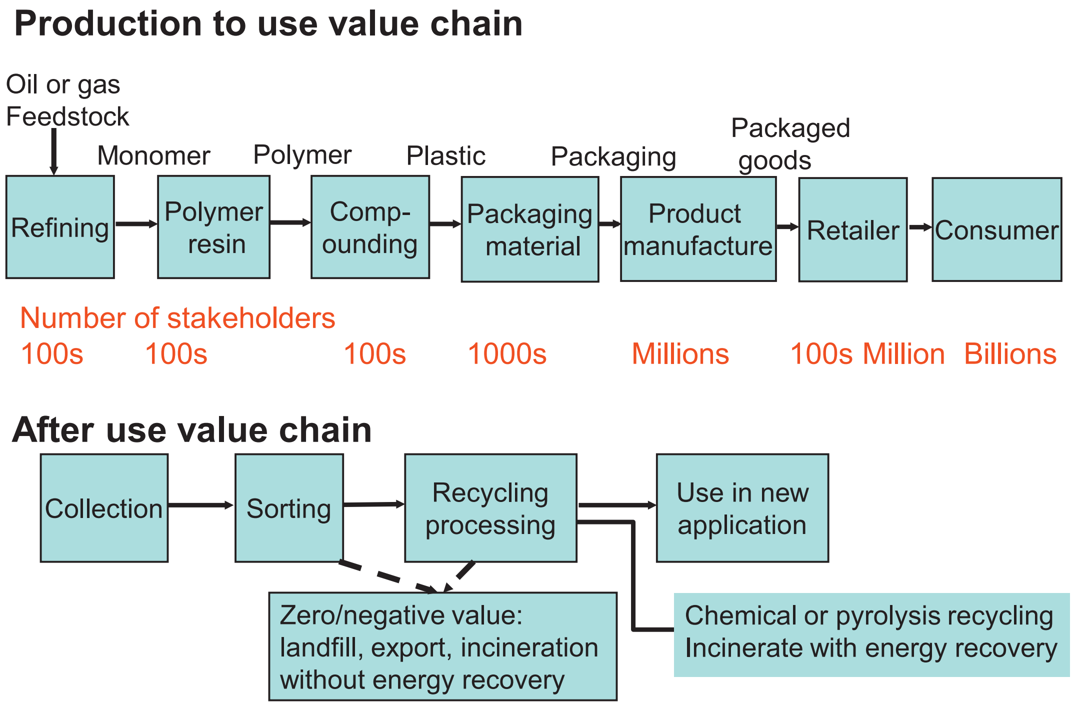


Figure 2 Plastics value chain and complexity (source: Expert Group).

properties of which can be adjusted according to the resin's molecular mass and structure and by using fillers, plasticisers, colouring, antimicrobials, antioxidants or other additives. The main resin types and their applications in Europe are shown in Figure 3, where the dominance of packaging as a primary driver of demand can be seen, as well as the fact that the polyolefin plastics (PE (polyethylene); PP (polypropylene); see Galli and Vechellio (2004)) are produced in the largest quantities for packaging use. The main polymers are sometimes identified by a 'resin code' as follows: 1, PET (polyethylene terephthalate); 2, HDPE (high-density polyethylene); 3, PVC (polyvinyl chloride); 4, LDPE (low-density polyethylene); 5, PP (polypropylene); 6, PS and EPS (polystyrene and extended polystyrene); 7, others.

Adapting the resin to the application requires the inclusion of additives to deliver the desired properties. These can include plasticisers, fillers, antioxidants, acid scavengers, light and heat stabilisers, lubricants, pigments, antistatic agents, surfactants and thermal stabilisers. Groh *et al.* (2019) examined the chemicals potentially released during manufacturing, use, disposal, and/or recycling of packaging and found 906 chemicals[6] probably associated with plastic packaging and 3377 substances that are possibly associated. Where a single plastic cannot deliver the required performance (e.g. in preventing oxygen transfer), multilayer composites may be necessary with each layer delivering one or more of the required functions (Hahladakis *et al.*, 2018). The final range of plastic packaging formulations in products is thus potentially huge which has serious implications for their recyclability (see later).

Mass production of plastics also uses high-throughput machines for injection or blow moulding, sheet formation, extrusion and other processes, which require fine-tuning of the plastic feedstock's properties to each machine's operation. This demands a high-quality standard for any plastic that is recycled, since different distributions of molecular mass in the basic resin and unknown levels of contamination by additives from previous use may be incompatible with these processing machines.

2.2.3 Priorities in design

Many factors contribute to the current low rates of reuse and recycling (see Chapter 4) including the difficulty of establishing efficient collection, sorting and recycling technologies, limits to the value of recyclate owing to quality issues, and the price of virgin material. Moreover, design has to optimise the choice of polymer and its additives to a wide range of health, hygiene,

[6] Of the 906 chemicals probably associated with plastic packaging, 63 were ranked highest for human health hazards and 68 for environmental hazards in the harmonised hazard classifications assigned by the European Chemicals Agency, and 7 classified in the EU as persistent, bio-accumulative and toxic.

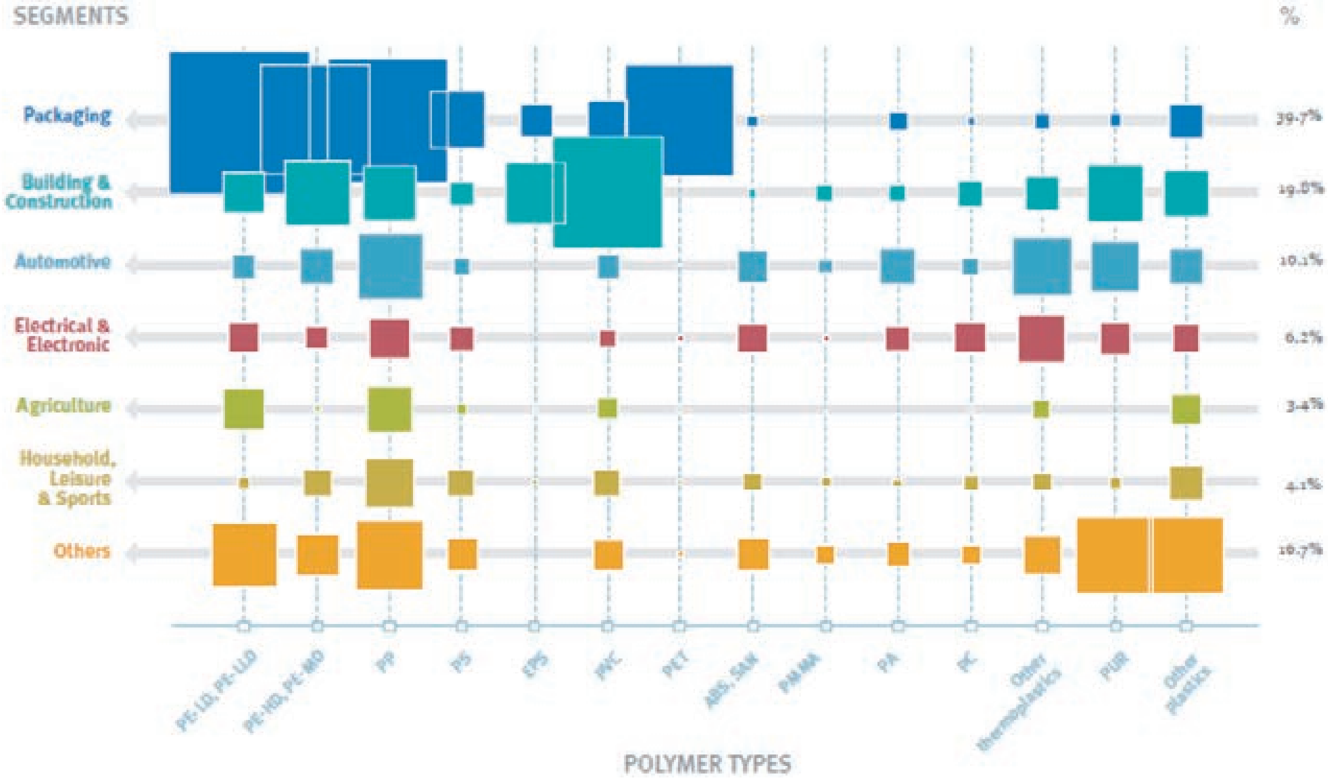


Figure 3 Plastics use in Europe in 2017 by industrial sectors (amended from Plastics Europe, 2018). PE, polyethylene; LD, low density; HD, high density; PP, polypropylene; PS, polystyrene; EPS, extended polystyrene; PVC, polyvinyl chloride; PET, polyethylene terephthalate; ABS, acrylonitrile butadiene styrene; SAN, styrene acrylonitrile; PMMA, Polymethyl methacrylate; PA, polyamide; PC, polycarbonate; PUR, polyurethane.

shelf life, transport and other requirements, as well as the attractiveness of the offer (shapes, colours, designs) to consumers. Designers have a wide range of materials to choose from and the effect of these on the recyclability of the package may have low priority. An example of this potential conflict can be seen in the spread of opaque PET (Box 2).

Shifting from the current linear thinking to a more circular system for packaging plastics would require end-of-life criteria to be incorporated from the design stage; and to factor in the recyclability of the main resin, the effects of additives, of colouring and transparency, and on the ability to separate where there are different materials used in a single product (e.g. tops of bottles, layers where laminates are involved). Guidance on these aspects is widely available (e.g. Box 3) but the policy challenge is how to incentivise manufacturers and users of plastic packaging to pay more attention to these factors, and related issues including standards, monitoring and enforcement. This is a primary objective of the European Commission's current policy development.

2.3 European Union current policy debate: the focus on 'single-use plastics'

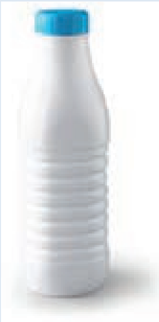
In parallel with actions at the global level (section 2.1), the European Commission's 2015 circular economy package included plastics as one of its priority sectors, and the Commission has since proposed measures to support a more circular use pattern (EC, 2018a). Action on 10 items of SUPs has also been taken (EC, 2019), based on detailed impact analyses (EC, 2018c).

A primary objective of policy is to reduce or eliminate leakage of plastic waste into the marine environment where globally mismanaged plastic waste along coasts and rivers in the Asian and African continents comprise the largest source (Jambeck *et al.*, 2015) with the EU and USA the source of just 2% of the total. Sea-based sources include discharges from ships, fishing activities and aquaculture[7] where much of the material sinks but remains, causing unseen effects to marine life through entanglement (ghost nets) and other obstruction. In Europe, land-based sources of marine plastics include loss from agriculture (e.g. plastics used for mulching)

[7] Fishing gear is an important source of marine pollution (and entanglement — see Annex 2) and separate measures are underway to ensure that waste is returned to port reception facilities and not abandoned at sea.

Box 2 Opaque PET: a conflict between producer priorities and recyclability (KDV, 2017)

Opaque PET is a problematic material for recyclers as it is difficult to distinguish from other materials such as (transparent) PET, PVC and HDPE; yet unlike those materials it is poorly recyclable owing to its opacifier coating. Previously, opaque PET was used in small volumes, allowing it to be absorbed within standard PET waste streams. However, rapid growth in its use (up 45% from 2014 to 2017 in France), notably for cosmetics and dairy products, has led it to becoming a disruptive material that degrades the quality of recyclates. Despite this, plastic producers continue to favour opaque PET because it is up to 20% to 30% cheaper than HDPE, and up to 20% lighter for specific applications.



Producers of opaque PET also benefit in EPR schemes where charges are related to weight (Chapter 3), since it is lighter than alternatives such as recyclable HDPE. Producers of opaque PET thus pay less even though the material is not recyclable. Some current market incentives can thus reward producers for disrupting the recycle system, showing that market signals can fail to incentivise producers to take into account the end-of-life stage of packaging.

Box 3 Designs/materials to be avoided to improve recyclability of packaging (WRAP, 2019; Recoup, 2017)

1. Metal closures on plastic bottles
2. Black plastic
3. Coloured or opaque PET
4. Compostable/ oxy-degradable plastics
5. Sleeves covering more than 60% of the bottle
6. Multilayer laminates
7. Non-removable film lids, PVC and silicone materials.

(Reasons and alternatives provided in the guidance documents.)

Table 1 Top 10 SUP items found in beach surveys (JRC, 2017)

Ranking	Item
1	Drinks bottles, caps and lids
2	Cigarette butts
3	Cotton-bud sticks
4	Crisp packets/sweet wrappers
5	Sanitary applications
6	Plastic bags
7	Cutlery, straws and stirrers
8	Drink cups and lids
9	Balloons and balloon sticks
10	Food containers including fast-food packaging

but are dominated by packaging, with plastic packaging comprising up to 80–85% of beach litter (EC, 2018b).

Beach surveys show that the dominant source of litter is 'single-use plastics' (e.g. crisp packets, cotton-bud sticks, containers), with the 10 most commonly found SUPs (Table 1) making up 86% of the plastic found. Experience from the many regulatory actions around the world to ban or charge for plastic bags[8] suggests that reducing the use of SUP also reduces littering and input into the marine environment[9]. The Commission thus decided to focus on these 10 items and develop regulatory options to reduce their use, improve their recyclability and reduce littering.

The Commission's estimates are that these 10 groups leak 15,600 tonnes per annum from the EU and contribute to the 75,000–300,000 tonnes of microplastics estimated to be in EU waters (Jambeck *et al.*, 2015). The environmental impact of each of the 10 SUPs has been estimated as shown in Table 2 (JRC, 2016).

The Commission's analysis notes that there are measures underway in related directives such as the increased waste recycling targets for plastic packaging: 50% by 2025 and 55% by 2030. Moreover, commitments to reducing marine litter are to be found in the regional marine pollution conventions and the Marine Strategy Framework Directive (Box 4). The specific issue of deliberate addition of plastic microbeads to cosmetics, paints, detergents and some other products is also being addressed through the Registration, Evaluation, Authorisation, Restriction of Chemicals (REACH) Directive (EC 1907/2006).

The Commission analysed the four policy options for reducing the environmental impact of SUPs in Table 3. Option 2d offered the largest improvement (74–82% reduction) in litter which also translated to the largest

[8] https://www.reusethisbag.com/articles/where-are-plastic-bags-banned-around-the-world.
[9] In Ireland the introduction of a tax on plastic shopping bags resulted not only in a 90% reduction of plastic bags provided in retail outlets (Convey *et al.*, 2007) but also in a marked decline in bags found on beaches.

Table 2 Assessing the risk of 10 SUPs on various aspects of environmental impact (JRC, 2016)

	Entanglement of marine wildlife	Ingestion by marine animal	Pollution of marine waters (chemicals release, microplastics)	Transport of invasive species	Microbial contamination	Economic impacts, tourism	Economic impacts, fisheries	Potential human health impacts
Drinks bottles, caps and lids	+	++	+	+++	+++	+++	+	+
Cigarette butts	-	+++	+++	+++	+++	++	++	+
Cotton-bud sticks	-	+++	+	+++	+++	++	+	+
Crisp packets/ sweet wrappers	+	+++	+	+++	+++	+++	++	+
Sanitary applications	+	++	++	+++	+++	+++	++	+
Plastic bags	+++	+++	+	+++	+++	+++	+++	+
Cutlery, straws and stirrers	+	+++	+	+++	+++	++	+	+
Drink cups and lids	+	++	+	+++	+++	+++	+	+
Balloons and balloon sticks	+	+++	+	+++	+++	+++	++	+
Food containers, fast-food packaging	++	++	+	+++	+++	+++	++	+
Fishing gear	+++	++	++	+++	+++	+++	+++	+

Box 4 Existing framework for addressing marine plastic pollution

The **Marine Strategy Framework Directive** has a target to achieve Good Environmental Status where (*inter alia*) 'marine litter *does not cause harm to the coastal and marine environment*'. This has been clarified as when litter and its degradation products present in, and entering into EU waters do not cause harm to marine life and damage to marine habitats, do not pose direct or indirect risks to human health or lead to negative socio-economic impacts (Galgani *et al.*, 2010).

Marine litter is also included in the amended **Waste Framework Directive**. It is recognised that marine litter (in particular plastic waste) originates to a large extent from poor solid waste management, littering by citizens and a lack of public awareness. Therefore, specific measures to reduce marine litter are requested in waste prevention programmes and management plans. Strategies and measures should be updated every 6 years, and reporting is obligatory from 2018.

The **regional marine pollution conventions** also contain '**Action Plans on Marine Litter'** which require use of best environmental practice for waste prevention and management; reduction of sewage and storm water related waste, including microparticles; incentives for reducing littering (e.g. reducing use of single-use items); consideration of environmental impact in products (e.g. phase-out of microplastic use, more sustainable packaging) and other measures.

saving in full environmental costs, but there was a substantial increase in waste disposal costs, so that the optimum balance between costs and benefits was selected as option 2c.

The Commission's objective is to have all plastic packaging placed on the EU market as reusable or recyclable by 2030. Within that, the Single-Use Plastics Directive (entered into force July 2019) includes the following.

- A **ban on selected SUPs** for which less environmentally damaging alternatives exist on the market: cotton-bud sticks, cutlery, plates, straws, stirrers, sticks for balloons, as well as cups, food and beverage containers made of expanded polystyrene and on all products made of oxo-degradable plastic (see Chapter 6).
- **Measures to reduce consumption** of food containers and beverage cups made of plastic and specific marking and labelling of certain products.
- **Extended producer responsibility (EPR) schemes** covering the cost to clean-up litter,

Table 3 Costs and benefit analyses of four policy options for SUP reduction (EC, 2018b)

Item	Sub-option 2a	Sub-option 2b	Sub-option 2c	Sub-option 2d
Cigarette butts	Information campaigns Voluntary action	Information campaigns Voluntary action EPR: cost of litter	Information campaigns Voluntary action EPR: cost of litter	Information campaigns Voluntary action EPR: cost of litter Label Reduction target (30% by 2025, 50% by 2030)
Drinks bottles	Information campaigns Voluntary action	Information campaigns Voluntary action EPR: cost of litter Product design	Information campaigns Voluntary action EPR: cost of litter Product design	Information campaigns Voluntary action EPR: cost of litter Product design Deposit–return scheme for beverage containers
Cotton-bud sticks	Information campaigns Voluntary action Label	Ban	Ban	Ban
Crisp packets	Information campaigns Voluntary action	Information campaigns Voluntary action EPR: cost of litter	Information campaigns Voluntary action EPR: cost of litter	Information campaigns Voluntary action EPR: cost of litter
Wet wipes	Information campaigns Voluntary action Label	Information campaigns Voluntary action Label EPR: cost of litter	Information campaigns Voluntary action EPR: cost of litter Reduction target (30% by 2025, 50% by 2030)	Best practice
Sanitary towels	Information campaigns Voluntary action Label	Information campaigns Voluntary action Label EPR: cost of litter	Information campaigns Voluntary action Label EPR: cost of litter	Information campaigns Voluntary action Label EPR: cost of litter Reduction target (25% by 2030)
Cutlery, straws, stirrers	Information campaigns Voluntary action	Information campaigns Voluntary action EPR: cost of litter Reduction target (30% by 2025, 50% by 2030)	Ban	Ban
Drinks cups and lids. Food containers	Information campaigns Voluntary action	Information campaigns Voluntary action EPR: cost of litter Reduction target (30% by 2025, 50% by 2030)	Information campaigns Voluntary action EPR: cost of litter Reduction target (30% by 2025, 50% by 2030)	Information campaigns Voluntary action EPR: cost of litter Reduction target (50% by 2025, 80% by 2030)
Balloons	Information campaigns Voluntary action Label	Information campaigns Voluntary action Label EPR: cost of litter	Information campaigns Voluntary action Label EPR: cost of litter	Information campaigns Voluntary action Label EPR: cost of litter
Balloon sticks	Information campaigns Voluntary action Label	Information campaigns Voluntary action Label EPR: cost of litter	Ban	Ban

EPR, extended producer responsibility applied to the producer of the packaged products (Chapter 3).

applied to products such as tobacco filters and fishing gear.

- A 90% separate **collection target for plastic bottles** by 2029 (77% by 2025) and the introduction of design requirements to connect caps to bottles, as well as a target to incorporate 25% of recycled plastic in PET bottles from 2025 and 30% in all plastic bottles as from 2030.

Against this regulatory background, the Expert Group considered that aspects where scientific input may assist the policy process include the following.

- The environmental impact of plastics which can inform the choice of priority targets for leakage reduction; this is summarised in Annex 2.
- Influencing the value chain towards a more circular model with greater consideration of end-of-life recycling potential is the objective of a revised EPR regime which is addressed in Chapter 3.
- The success of any policy will depend very much on the cost of waste disposal, the difficulty of recycling and the markets for recycled material (Chapter 4).
- Even in an improved reuse and recycling system, measures against littering and other aspects will still be influenced by consumer behaviour, as discussed in Chapter 5.
- Degradation of plastics that enter the environment and the use of non-fossil-fuel feedstocks (bio-based plastics) is discussed in Chapter 6.
- Targets for research and innovation are discussed in Chapter 7.
- Finally, a discussion of the implications of the Expert Group's scientific analyses for policy is presented in Chapter 8.

3 Extended producer responsibility

3.1 The rationale for extended producer responsibility

Neoclassical economics has yet to fully factor into prices the environmental costs of natural resource extraction, pollution and disposal of products at the end of their life. Such costs may arise from global issues such as climate change and resource depletion to individual short- or long-term effects on health of emissions or chemicals used in the products concerned[10]. Moreover, local externalities may arise from just the physical properties of plastic packaging such as blockage of drainage systems triggering flooding[11]. Such 'externalities' are borne by society at large or by future generations. Principles already exist to address these issues — for instance sustainable development seeks to protect the world and its resources for future generations, while the polluter pays principle states that the originator of environmental damage should bear the costs of avoiding and repairing that damage. ***EPR*** can be seen as one means of applying the polluter pays principle since it gives *producers responsibility (*financial and/or operational) for the treatment or disposal of their products when discarded after use. Assigning such responsibility can provide incentives to prevent wastes at source, promote product design for the environment and support the achievement of public recycling and materials management goals (OECD, 2001, 2016).

From a theoretical standpoint, the objectives of EPR applied to packaging plastics can be as follows.

- Environmental: to reduce environmental externalities (particularly waste leakage to terrestrial and marine environments, and greenhouse gas (GHG) emissions).
- Financial: to reduce the burden on public finances of costs that emanate from the need to dispose of products produced by companies.
- Conceptual: as a means of encouraging more sustainable products better aligned with the circular economy.

The mechanism is presumed to be that, if they have to bear all end-of-life costs, product manufacturers will have an incentive to apply science and plastic engineering to design products that are more easily collected and recycled after use. In turn, if demand for recycled products is increased, costs of production can be reduced by increased efficiencies of scale. Additionally, fees paid by producers and importers could be used to stimulate innovation in production technologies using recycled material, improve quality and reduce recycling costs to better compete with virgin feedstocks.

3.2 Current extended producer responsibility schemes in Europe

Surveys of EPR schemes applied to plastic packaging (IEEP, 2017) show considerable variability between Member States. The manufacturer of plastic packaging is generally charged a fee based on the amount of plastic packaging material brought to the market. These fees vary widely: there is a factor of over 10 difference between the €200 per tonne charged in Austria and the €15 per tonne charged in the UK (EAC, 2017), and the charges in Italy averaged €253 per tonne in 2018. In some EPR schemes, manufacturers are individually responsible for paying the fees; in others, they may delegate this responsibility to a producer responsibility organisation (PRO) and pay their fees to the PRO. Other differences relate to the following:

- the types of packaging covered;
- whether PROs have just financial responsibility or operational responsibility[12];
- whether different fees are charged for different materials; some charging systems do not differentiate between products on the basis of their recyclability; others include fees that are adjusted to their recyclability.

In their analysis, IEEP (2017) identified several weaknesses in existing EPR schemes.

[10] For example, endocrine-disrupting chemicals (EDCs) have been estimated (Trasande *et al.*, 2015) to contribute substantially to lifetime disease and dysfunction with costs in the hundreds of billions of euros per year. Groh *et al.* (2019) found that, among the 906 chemicals identified as potential additives in packaging plastics, 34 were recognised as EDCs or potential EDCs by UNEP. Zimmermann *et al.* (2019) also found that most plastic extracts from PP, LDPE, PS and PLA contained chemicals triggering at least one toxicological end point, including baseline toxicity, oxidative stress, cytotoxicity, oestrogenicity or anti-androgenicity (PET and HDPE did not).

[11] For example, a flood in Ghana as a result of blocked drainage cost the lives of 150 people and millions of dollars of damage (Jambeck *et al.*, 2018).

[12] Fully operational responsibility is typified by German packaging law which requires that companies selling goods (whether domestic or imported, and including on-line goods) must be registered for participation in a PRO which takes care of the recycling or disposal of any packaging material they sell. This is separate from the municipal waste-collection systems. PROs such as 'Green Dot' operate separate collection systems, sort and where possible recycle the waste. Paying fees to these intermediary organisations allows the packaging to be labelled as recyclable. On the other hand, some countries' PROs merely manage the EPR fees and outsource the handling of the waste to other organisations through contracts.

- Low charges to plastics manufacturers do not provide economic incentives to avoid waste or make packaging more easily recycled. For example, the low charges in the UK left over 90% of disposal costs to local government budgets (EAC, 2017).

- Collective PRO schemes average fees across producers, and dilute incentives for individual producers to be innovative.

- Current fees relate to the basic costs of waste management and do not reflect wider environmental costs such as GHG emissions or costs of environmental damage through leakage.

- Fees encourage waste management changes which minimise the costs of recycling and treatment rather than following wider sustainability or circular economy objectives.

- Most EPR schemes are based on a weight-related charge which favours product lightening, or switching to lighter materials, which may not be aligned with recycling objectives.

- Current EPR schemes lack any specific objective aimed at preventing leakage of packaging into the terrestrial and marine environments.

- EPR currently is applied to the producer of the packaged goods; it does not therefore extend to earlier parts of the value chain such as the companies producing the plastic resins themselves.

With respect to incentivising product designers to consider the need for recycling, EPR can contribute by differentiating between readily recycled materials and those that are difficult to recycle (**eco-modulation**). This has been applied to some extent in Italy and France (and most recently the Netherlands) where materials that can be effectively recycled to usable recyclates attract lower fees than difficult or impossible-to-recycle materials. Such eco-modulated fees can, in theory, take into account a range of product design criteria relating to their end-of-life use and environmental impacts, such as toxicity, durability, reusability, reparability and recyclability/compostability (EMF, 2017). Fees can also be reduced where producers take on direct responsibility for their end-of-life products: for instance, through collection, treatment or public awareness measures.

A review of 395 EPR schemes globally (Kaffine and O'Reilly, 2015) concluded that directly linking fees to a product characteristic was most likely to trigger design changes. Impacts of EPR on design and packaging recyclability are also encouraged by individual rather than by collective PRO schemes, since the shared responsibility in the latter (even though they may reduce transaction and monitoring costs) dilutes any incentive for individual producers to innovate to reduce waste and increase recycling.

The EC's SUP Directive extends EPR principles to cover clean-up costs, and sees a greatly strengthened EPR as a critical tool in moving the plastics value chain into a more circular system. In addition to full cost recovery, steep eco-modulation with a large difference between favoured and disfavoured materials and designs rewards redesigns to readily recycled materials and formats. The Italian CONAI-COREPLA system introduced in 1997 (CONAI-COREPLA, 2017; Stramare, 2013) includes consideration of not just recyclability but also the availability of local capacity to produce and use the recycled material, and can thus encourage improvements in local recycling infrastructure. With composite packaging, fees can reflect the ease/difficulty of separation and recyclability of the layers. Disruptive additives such as opacifiers can be penalised, along with packaging format, labels, glues, lids, etc. that disrupt sorting.

As the complexity of eco-modulation EPR schemes increases, however, the costs of monitoring and verification need to be weighed against the benefits. For instance, the Italian CONAI-COREPLA scheme decided, after conducting detailed LCA on overall environmental impacts of 59 different types of packaging, to group these into just four categories with the charges that will be applied from 2020 as follows[13]:

A: packaging with an effective and consolidated sorting and recycling chain from commerce and industry (€150 per tonne);
B1: packaging with an effective and consolidated sorting and recycling chain from households (€208 per tonne);
B2: packaging with a sorting and recycling chain in the process of consolidation and development (€436 per tonne);
C: packaging not sortable or recyclable with current technologies (€546 per tonne).

A key issue is whether EPR schemes should cover the full cost of externalities (disposal, recycling, cost of clean-up as well as to costs attributable to their GHG emissions) and aim specifically to create synergy with broader sustainability and circular economy objectives. If so, incentives are required to move up the waste hierarchy as specified in the Waste Management Directive (2008/98/EC) which prioritises prevention and reuse ahead of recycling. Priorities would be to first reduce the amounts at end-of-life, then increase the proportion

[13] http://www.conai.org/wp-content/uploads/2019/09/list of packaging contribution levels 2020.pdf

that can be reused, followed by recycling which in turn is higher priority than incineration or landfill (see also Chapter 8).

Ensuring the effectiveness of EPR schemes depends very much on the reaction of packaging producers, retailers and consumers. The convenience offered by many packaging formats can lead to significant market resistance to more environmentally friendly materials and designs. The willingness of industry to respond in a positive way to such measures is particularly critical and among the measures recommended by EMF (2016) for actions by companies is to ensure that, by 2025:

- problematic or unnecessary plastic packaging is eliminated;
- single-use packaging moves to new delivery models that promote reuse;
- 100% of plastic packaging is reusable, recyclable, or compostable;
- targets are set for post-consumer recycled content;
- common definitions and industry standards to be agreed on what materials are put into the marketplace;
- constructive engagement with governments on the need for improvements to waste management infrastructure, including the implementation of EPR schemes.

This Global Plastics Pact initiative has now 400 signatories which together are responsible for 20% of packaging plastics produced globally (EMF, 2019). The Pact has led to detailed plans to implement via national versions (e.g. the UK and European Plastic Pacts), and commitments by some leading consumer product companies, as illustrated in Box 5.

Box 5 Some national and corporate commitments under plastics pacts

A. UK plastic pact and roadmap for implementation (WRAP, 2018a)
This was one of the first national plastics pacts (announced in April 2018) with a vision of transforming the way that the UK makes, uses and disposes of plastic. We need to move away from a linear plastics economy towards a circular system where we capture the value of plastics material – keeping plastic in the economy and out of the oceans. The UK Plastics Pact brings together governments, businesses, local authorities, citizens and NGOs behind a common vision and commitment to a set of ambitious targets'.

Targets for 2025:
1. Eliminate problematic or unnecessary single-use packaging through redesign, innovation or alternative (reuse) delivery models.
2. 100% of plastic packaging to be reusable, recyclable or compostable.
3. 70% of plastic packaging effectively recycled or composted.
4. 30% average recycled content across all plastic packaging.

B. EUROPE-WIDE (Plastics Europe, 2020)
A new European Plastics Pact will be launched in March 2020 to drive towards a circular economy. Signatories to the pact are expected to be required to focus on goals in four areas:
1. (Article 5). '*Designing all single-use plastic products and packaging brought to the market by participants to be 100% recyclable and to be reusable where possible and sustainable, and in all cases to be recyclable by 2025.*'
2. (Article 6). '*Shifting towards a more responsible use of single-use plastic products and packaging, by eliminating unnecessary use, by introducing reuse models and by using alternatives that are safe and more sustainable, aiming for a reduction in plastics use of 20% by 2025.*'
3. (Article 7). '*Creating sufficient collection, sorting and recycling capacity by 2025 to increase recycling of all single-use plastics and packaging by at least 25 percentage points- as long as the result is more ambitious than the targets in the EU regulatory framework- and to reach a quality standard that matches the market demand for recycled plastics.*'
4. (Article 8). '*Achieving the highest possible percentage of use of recycled plastics (by weight) by 2025, reaching at least 30% average recycled content across all single-use plastics products and packaging.*'

C. Unilever's 2017 commitment
(https://www.hul.co.in/Images/unilever-commits-to-100-recyclable-plastic-packaging-by-2025_tcm1255-497353_1_en.pdf)

Aims:
1. Ensure that 100% of plastic packaging will be designed to be fully reusable, recyclable or compostable by 2025.
2. Commitment to increase the recycled plastic content in own packaging to at least 25% by 2025 and to reduce its weight by one-third by 2020 and halve the waste associated with the disposal of own products by 2020.

Changes required:
1. Design for Recyclability guidelines are applied for example, modular packaging, design for disassembly and reassembly, wider use of refills, recycling and using post-consumer recycled materials in innovative ways.
2. Driving systemic change in circular thinking at an industry level.
3. Working with governments to create an environment that enables the creation of a circular economy, including the necessary infrastructure to collect and recycle materials.
4. Working with consumers to inform on different disposal methods (e.g. recycling labels) — and collection facilities.
5. Exploring radical and innovative approaches to circular economy thinking through new business models.

4 Technical factors in recycling

4.1 Current situation

Plastic packaging is almost entirely formed by thermoplastic polymers, namely by polymers that are in principle recyclable through simple thermo-mechanical processes in mild conditions (Hestin *et al.*, 2015; Dahibo *et al.*, 2018). A large number of LCAs have been performed, and meta-analyses (e.g. WRAP, 2018b) conclude that plastics recycling has a significantly smaller GHG footprint than plastics incineration or landfilling. Where a clean single-resin feedstock is available, recycling waste to a new product can save up to 1.4 tonnes of carbon dioxide equivalent for each tonne of plastic (Denkstaff, 2011; CIEL, 2019), in contrast with the additional emissions generated if such wastes are landfilled or incinerated (especially when without energy recovery). Tijm and Verrips (2019) estimate that these potential benefits of recycling plastic packaging into a more or less equivalent product are between 11 and 42 eurocents per kilogram. Achieving these potential savings in practice, however, may be hampered by the additives, impurities from other resins, and other factors addressed in this section. In particular, recycling waste plastics to be reused as a raw material for new products introduces many technical challenges since much of the processing equipment is designed for feedstocks of virgin polymers of specific molecular weight distributions. Often moulding or blowing or film preparation is reliant on precise control of the polymer and its additives, with processing machines sensitive to small changes in melting/softening points. Unless very pure polymers can be provided by the recycling process, therefore, recycled polymers are limited not just by price but also their processability. Moreover, recycling for food packaging is generally forbidden because of fears about contamination (see Box 6).

There are three main approaches to plastics recycling (Hopewell *et al.*, 2009; Singh *et al.*, 2017; Valavanidis, 2018).

1. **Mechanical recycling** melts down the waste and reprocesses into pellets. Plastics have to be sorted by type and separated into the different polymer types; then crushed, washed and dried. Multiple recycling is limited by the scission of the polymer chains through heating and loss of properties relative to virgin material. **Containers for liquids** (e.g. PET beverage bottles or HDPE milk bottles) are readily recyclable since these are easily recognised by consumers for separate collection or can be easily separated by screening techniques. Industrial recycling processes are thus well-established and economically viable for PET, HDPE and, at a smaller scale, PP. The market for these specific recycled plastic pellets is buoyant, with demand exceeding supply[14].

   Recycling of flexible packaging is more difficult. Firstly, there will be a mixture of materials (primarily LDPE, PP and some HDPE) where separation can be very difficult; secondly owing to the prevalence of multilayer and multi-material films; thirdly because of the contamination by food residues, dirt, etc. As a result, only mono-material films of large size (constituting only a minor proportion of collected flexible packaging) are commercially recyclable, and even recycling of mono-material films is made difficult by dark colours[15] which hinder their separation using near infrared (NIR) spectroscopy. Smaller items (typically smaller than 5 cm) are not separated owing to difficulties in polymer recognition and separation, although, in some cases, fractions of the collected flexible packaging can be separated as mixed polyolefinic material, which can be used for low-added-value applications.

2. Although not currently in use at scale, **chemical recycling** can process flexible packaging and more difficult-to-recycle packaging (Rahimi and García, 2017). Chemical recycling aims to depolymerise the polymer to the starting monomers which can then be used to make a new polymer. It is thus essential to ensure the waste comprises the same basic polymer and pre-sorting is important. Pilot-plant processes are available for PET (through chemolysis, namely glycolysis or methanolysis), and for simple depolymerisation of polystyrene. Chemical recycling to achieve full depolymerisation, namely purification of monomers to re-produce the polymer in a closed-loop system, are being researched (e.g. Rahimi and García, 2017; Christensen *et al.*, 2019).

3. Even if chemical recycling into monomers is less demanding on purity than mechanical processes, it still requires pre-treatment. On the other hand, for **feedstock recycling** there are only low demands on the purity of the input. There are two principal methods for feedstock recycling (Punkinen *et al.*,

[14] Owing to the shortage of polymeric recyclable waste, COREPLA (the Italian Consortium for the Collection and Recycling of Plastic packages) regularly holds auctions for their sale.
[15] Black plastic is not only an interference with the recycling sensors, but is also more likely to contain chemical contaminants that derive from the use of waste plastic from electrical goods as a source of plastic packaging (Turner, 2018).

Box 6 Constraints and technical barriers to recycling

There are many barriers to effective recycling (see for example OECD, 2018a) including the following.

- The wide **range of different types of plastic** used in disposable products and packaging. (PP, PE, PET, PS, etc.). There are seven major thermoplastic polymer types used in packaging, but additives to produce the desired colour, shape and texture all affect the basic properties. Some plastics may be used without additives (e.g. some LDPE) while others contain more additives than polymer resin. Even simple polymers such as LDPE or HDPE can be produced with major differences in molecular weight distributions and structure to adjust their properties for a specific processing and application. Thus, sorting into recyclable waste streams of predictable and desirable properties is difficult. Outside of the separate collection of PET beverage containers, **packaging plastics** often end up as 'mixed' waste with very low, zero or even negative value which accounts for the attractiveness of exporting to countries with low costs but unclear recycling and disposal methods. Even the same material may involve a need to separate: for example, containers such as tubs and trays are 'injection-moulded' and contain additives that interfere with recycling of plastic bottles which are 'blow-moulded'. In practice, even the polyolefins have complications whereas other plastics are often not recyclable.
- **Contamination**. Plastic packaging is in contact with many potential contaminants- residues of the contents, labels and caps of different materials, additives used in the plastics that are incompatible with recycling (opacifiers, oxidants, etc.), or additional contaminants inherited from using plastic waste as the raw material for plastic packaging (e.g. from waste electronic equipment (Turner, 2018)). Such contamination not only may affect the recycling process but is also particularly important if recycled plastic is to be subsequently used in food packaging. The safety of food contact materials requires evaluation as chemicals can migrate from packaging into food, and tests for approval are understandably strict. Specific recycle processes need authorisation of the processes used to recycle (EC 282/2008) after evaluation of risk by the European Food Safety Agency. An example is that in 2015 the Agency assessed two processes used to recycle HDPE plastic bottles for use as food contact materials. The Agency concluded that using recycled HDPE in trays for dried whole fruits and vegetables is safe, but could not confirm safety for plastic milk bottles and trays for animal products. Thus the barriers that need to be overcome are substantial and make using fresh virgin material preferable.
- **Composites** that have different types of material in the same product. For instance, a plastic bag with a foil lining or a disposable coffee cup made of paper with a plastic lining. These are especially difficult and expensive to separate.
- **Degradation of the resin molecule** in the recycling process. The well-characterised molecules of similar length in a new plastic will undergo some breakdown every time the plastic is melted, thus affecting the properties and creating uncertainties over the remaining properties. Since many of the expensive packaging producing machines require very precise physical properties, such uncertainties render recycled feedstock unusable in replacing virgin materials, and thus most recylates are 'downcycled' to lower-grade products such as jacket fill, fleece, carpet, toys or plastic lumber which are not recycled further. Unlike glass or aluminium, plastic recycling does not 'close the loop' in the circular economy sense since most post-consumer waste is not used for new containers. At present, the only significant 'closed-loop' operation in Europe is for PET where approximately 9% of the feedstock for new bottles is derived from recycled PET.
- **Recycling information is misleading and labelling inconsistent.** Some products use a resin code to identify the basic polymer in the plastics (section 2.2). However, this does not mean that the material is recyclable- let alone whether it will be recycled. As the Society of the Plastics Industry notes, '*The code was not intended to be - nor was it ever promoted as - a guarantee to consumers that a given item bearing the code will be accepted for recycling in their community.*' This is discussed further in Chapter 8.

2017). **Pyrolysis** is a thermal decomposition in the absence of air whereby plastic solid waste is converted into a wide range of products including monomers, paraffins, olefins, and gas. **Gasification** (in the presence of oxygen, air, oxygen enriched air and/or steam) converts the mixed plastic into synthesis gas (syngas) and fuel gas. Syngas is composed of carbon monoxide, hydrogen and small amounts of hydrocarbons and can be cleaned and further processed into a variety of final products, such as methanol, dimethyl ether, gasoline, synthetic methane chemicals and polyolefin production. Until now, feedstock recycling (as well as chemical recycling) has not been economically attractive, but the first commercial plants are entering operation (e.g. Recycling Technologies' Plaxx process in Swindon, England, and in Perth, Scotland). Another company (Neste) is developing a waste-plastic-based pyrolysis process at an industrial scale with a target of converting more than one million tonnes of waste plastic by 2030[16].

Other approaches have also been researched — for example, dissolving polymers into bio(fuels) to enrich the fuel (e.g. Mohammadi *et al.*, 2012; Yamane and Kawasaki, 2012), or using syngas in enhanced oil recovery (e.g. Fink and Fink, 2002). Other potential methods are at the development or demonstration phase including depolymerisation (see Box 9), super-critical fluids (e.g. Goto, 2009) and through dissolution (e.g. Zhang *et al.*, 2010).

4. Particularly when the previous methods are difficult, a common method is to exploit the high energy content of plastics and incinerate with energy recovery.

In current practice, barriers to recycling (as in Box 6) increase costs and may render any recyclate either more expensive than virgin resin, or unable to meet the quality standards required by the processing methods used or those of the end product. In these cases, currently option 4 of energy recovery is the most economic means of extracting some residual value.

[16] Neste Company press release, 18 July 2018.

4.2 Potential for improving recovery and sorting of post-consumer plastic

Primary objectives for improving the recycling system are that the amounts of end-of-life packaging that is recycled increases and, at the same time, the proportion of 'closed-loop' recycling is increased. 'Design for recycling' criteria (cf Box 3) for the production of plastic packaging that may improve the technical and economic viability of plastics recycling include the following.

1. Limit multi-material packaging based on different and immiscible polymers or other materials (mainly aluminium and paper). Even though the involved layers are in principle recyclable, their adhesion makes recycling unfeasible. For instance, rigid packaging with layers of PET and polyamides could be banned or assigned higher charges in EPR schemes.
2. Limit dark colours, which make polymer recognition and sorting by NIR difficult.
3. Limit covering labels that make polymer recognition and sorting by NIR difficult.
4. Prefer for packaging design, plane and slightly angular surfaces, which make easier polymer recognition and sorting by NIR.
5. Limit the number of polymers to be used for specific applications. For example: for rigid packaging: PET, HDPE, PP and possibly PS; for flexible packaging: LDPE and PP.
6. Avoid as much as possible use of specialty copolymers and blends of these polymers.
7. Use only one kind of polymer (e.g. LDPE) for packaging items whose maximum size is lower than 5 cm.
8. Clear labelling which accurately states the main resin and its recyclability and conditions necessary for recycling.

Taking a systems approach has to recognise that the diversity of plastics in a mechanically separated waste stream may still lead to substantial quantities that cannot be properly sorted into a saleable material. This currently goes to landfill, incineration or export, but adjoining a second process to the mechanical sorting would increase the recovery options. The concept of such an 'advanced plastics reprocessing facility' is shown in Figure 4, where the mechanical recovery stage capable of separating 52% of the incoming plastic waste is supplemented by chemical recycling which can extract valuable materials from an additional 43%, so that only 5% of the initial waste remains to be sent to landfill. An additional option would be to replace virgin fossil feedstocks in existing petrochemical infrastructure by plastic waste which, in recent detailed evaluations (Thunman *et al.*, 2019), offers an economically viable alternative to current disposal methods. All such methods, however, require proper life cycle assessments to establish that there is a net environmental benefit in terms of reduced emissions and resource consumption, as well as their economic viability.

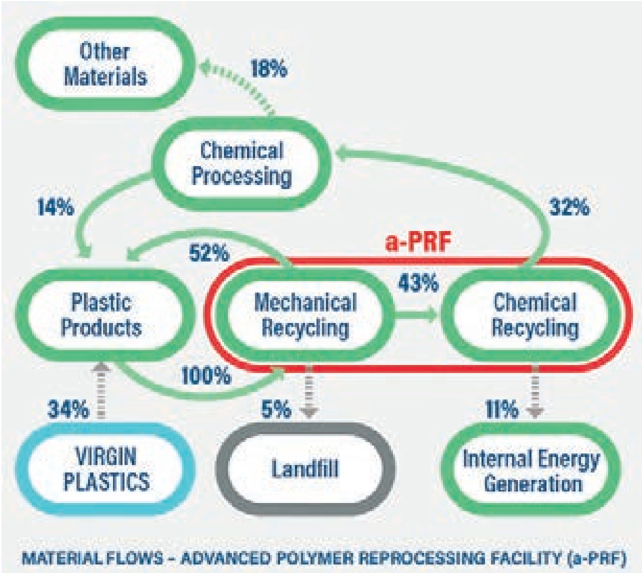


Figure 4 Flow diagram for an advanced plastics reprocessing facility (source: Recycling Technologies, 2019).

5 Consumer behaviour

5.1 The role of consumers

Most of the plastics used in packaging reach their end-of-life in the hand of individual consumers who determine what happens with the container, film or other item. However, the importance of consumer decisions is not just at the end-of-life. They may play a critical role in other parts of the system (Figure 5): for instance, whether to purchase a plastic product (e.g. bottled water or packaged vegetables), or whether to reuse a bottle or bag rather than throw it away, as well as the consumers' level of support for regulations aimed at reducing plastic waste and littering.

Direct influences on the amount of plastics leaking into the environment arise both from purchase decisions and from post-use behaviour. Ideally, people should be aware that when they purchase or accept any plastic good, this brings with it a share of the responsibility for avoiding plastic pollution. However, consumers' choice of actions may be highly restricted by decisions outside their control. These include provision of unnecessary packaging by manufacturers and retailers, which may require conscious effort by the consumer to avoid, shortcomings in the collection systems provided by local governments, and leakage in the treatment of collected waste. Nevertheless, without consumer support and cooperation, efforts to reduce plastic leakage into the environment are likely to be at least impeded if not futile. The factors involved in motivating sustainable consumption among consumers and effecting behavioural change have been extensively studied (e.g. Jackson, 2005) and social and behavioural research is also relevant in the current debate on measures to reduce plastics pollution (Pahl and Wyles, 2016).

5.2 Influences on consumer attitudes

Consumer attitudes are highly influenced by **media and communication messages**. Broadcasting of marine plastics pollution in high-profile programmes such as The Blue Planet has had substantial impacts on public awareness (e.g. Hartley *et al.*, 2018). On the other hand, media coverage of photogenic images may oversimplify the issues as well as seek to apportion blame which can lead policy-makers to seek simple short-term actions (a 'quick fix') rather than address the underlying problem. Elements of this have already been seen in measures to restrict plastic straws rather than address the primary use of difficult-to-recycle beverage containers and the limited recycle infrastructure.

The media also play a critical role in communicating policy. Traditional media already cover a spectrum ranging from strong support for environmental protection to principled opposition to what may be seen as restricting the freedom of the individual. Measures to improve recycling thus need to be framed in ways that avoid opposition from such diverse viewpoints. Meanwhile, the growth of social media has eroded historical quality-control mechanisms, blurring the distinction between fact-based reporting, opinion, deliberate distortion or entirely fabricated stories. Any social campaign will need careful planning and managing of a sustained traditional social media presence, for example by incorporating the messages into popular TV shows, soap operas, and the messages of social media influencers.

The power of social media can be illustrated by the opposition to the use of plastic microbeads, whose introduction in cosmetics and other household goods was an internal decision by manufacturers who did not consider their inevitable release to the environment as a problem (neither were there regulations restricting such plastic flows into the environment). When users discovered through social media their use in cosmetics, toothpaste, etc., concerns rose over their potential negative environmental impact, and social media campaigns led to their restriction or voluntary withdrawal in several countries. Media coverage of such issues, together with surveys showing the extent to which plastic fragments such as fibres have spread throughout the environment, has also led to general concerns over wider contamination. For instance, one survey in Germany showed that most of the population feels strongly (39%) or moderately (23%) contaminated by plastic particles in food and drinking water (BMUB/UBA, 2016).

Several areas of psychological research (Box 7) help better understand factors influencing consumer attitudes and responses to different policy changes.

Among the factors introduced in Box 7, public attitudes are greatly influenced by **perceptions of risk**. News about risks may trigger a rapid behavioural change by some (e.g. to news of microplastics in bottled drinking water) but such responses are likely to be transient. It has long been recognised that people are likely to perceive (environmental) risks as more acceptable where associated with benefits, where any risk is delayed or gradual, and when risks are less observable or tangible (Slovic, 1987). In the analysis by the Science Advice for Policy by European Academies (SAPEA)'s overview of microplastics (SAPEA, 2018), sources from car tyres or synthetic fabrics constitute examples where public perception is very low, evidence of human health impacts lacking and where uses (vehicles and clothing) have a major benefit. Such sources are likely to be seen as more 'acceptable' than sources such as microbeads where any benefits are obscure.

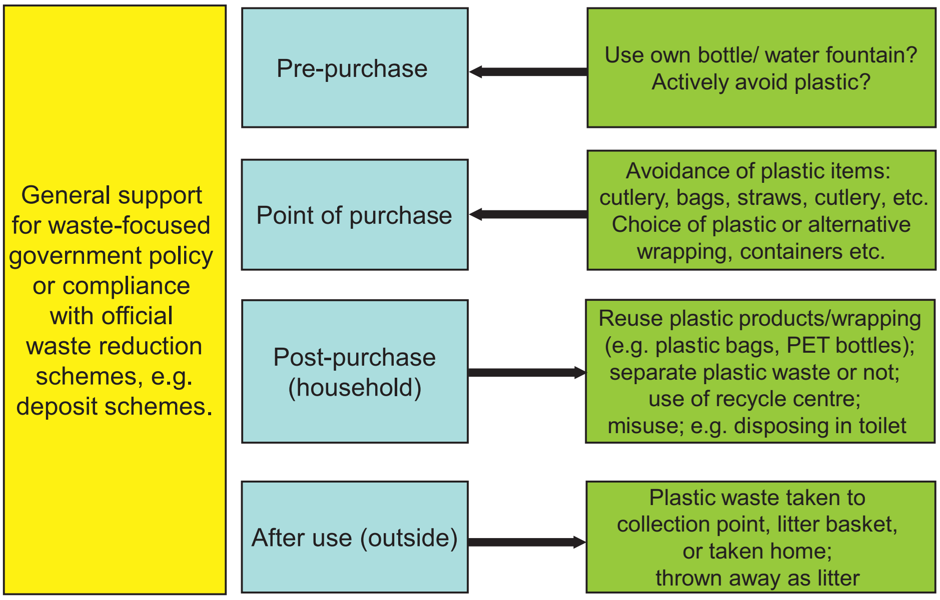


Figure 5 Examples of consumer influences (source: Expert Group).

In general, people do not buy and leak plastic for the express purpose of harming the environment; rather, they do so because of lack of choice, inadequate collection systems, or lack of knowledge of, or indifference to, the consequences of their behaviour. The factors in Box 7 of **perceptions of responsibility and of control** and the **efficacy of actions** are important. Responsibility perceptions may be multi-faceted: Hartley *et al.* (2018) found that the public perceived retailers, industry and government as most responsible for marine litter (while at the same time least motivated to reduce it), which could reduce personal motivation to act. Nevertheless, personal responsibility remains (Steg *et al.*, 2012) and can be strengthened by information and communication measures, or by influencing social norms through rules. The concern that one's own actions should be worthwhile (efficacy) means that positive behaviour is encouraged where there are convenient alternative options; for example, for reusing everyday items such as cups, bottles or plastic bags, and for disposing of waste easily (Steg and Vlek, 2009).

Consumer behaviour is also a critical factor in determining the effectiveness of packaging in reducing food waste (Wikstrom *et al.*, 2019) since packaging poorly aligned with consumers' needs and use could lead to increased waste through spillage, or encourage purchase of amounts that are too large or impulse buying. Studies of the GHG emissions from food waste and the packaging involved show that in some cases the GHG footprint of the packaging greatly exceeds that of the packaged product (Heller *et al.*, 2018), so that carefully assessing the needs and responses of consumers to packaging (or no packaging) is necessary if a net benefit from the standpoint of food waste is to be achieved. For instance, plastic wrapping of vegetables and fruit may be aimed at reducing food waste by extending shelf life but whether this justifies the resource and energy costs of the packaging and its disposal may depend on consumer behaviour. Packaging limits the consumer's choice of quantity and if it encourages over-purchasing, the net effects on food waste may well be negative.

Given the wide range of factors above and the vast range of individual characteristics, any policy must be multi-faceted to be effective. Some consumers may be motivated by information, others by rules that set out the social norms, yet others by reward systems that change perceptions of the balance of costs and benefits. A 'one size fits all' approach may be difficult to devise. As noted by Ritch *et al.* (2009), information alone – even when simple, accurate, well presented and action oriented – can be insufficient to shift behavioural patterns, and there is often a substantial gap between the degree of concern that consumers express about the environment and their behaviour[17].

Consumer thinking is not an isolated factor and interlinks with the attitude of the manufacturers and retailers, especially in assigning blame. Producers may assign their decisions to the mantra of 'meeting consumer needs' or 'responding to consumer choice',

[17] For example, a survey of Irish consumers found that while 30% of consumers claimed to consider the state of the planet when they decided what to buy, only 3% acted on those thoughts (National Consumer Council, 2008).

Box 7 Psychological research relevant to consumer behaviour

Behavioural studies suggest that **concern, perceived behavioural control, values, attitudes, emotions and personal and social norms**, as well as **knowledge and awareness**, influence intentions and behaviour.

Individuals vary in their perceptions of the seriousness of environmental risks, and these have been associated with different types of **personal value** (Steg *et al*., 2012):

- hedonic values (striving for pleasure and reduction of effort);
- egoistic values (improving or securing one's resources);
- altruistic values (caring about others); and
- biospheric values (caring about the quality of nature and the environment).

Given this diversity of individuals' mindsets, measures aimed at changing consumer behaviour should either target people with different value systems and reasoning patterns, or should aim to change the value systems and reasoning of people. Simple measures based on 'one size fits all' are unlikely to be effective.

Altruistic and biospheric values tend to be associated with higher perceptions of global environmental risks while hedonic and egoistic values are not. Attitudes to risks also depend on whether the individual applies '**consequentialist**' reasoning and perceives the risks as acceptable when the benefits of actions causing these risks are seen as high. On the other hand, a '**deontological**' reasoning would base risk assessment on the rightness or wrongness of actions *per se.*

Knowledge in itself is typically *not sufficient* to motivate pro-environmental behaviour by individuals (see Abrahamse and Steg, 2013; Hornsey *et al*., 2016; Ünal *et al*., 2018) or by organisations. Behavioural change requires a motivation to change *and* practical know how (skills) on possible responses.

Awareness and **concern** are predictors of behaviour and **personal norms**, but people also need to feel capable of change (Steg, 2016). Where awareness of the issue is associated with a belief that one's own actions will help reduce the problems (a sense of control and that action will bring results — outcome efficacy), this may strengthen a sense of moral obligation and responsibility (personal norms). Personal factors work together with **situational factors** which include **economic constraints, social pressures, and opportunities for alternative actions** (Kollmuss and Agyeman, 2002).

Many behaviours are **habitual**, and thus resistant to change since they are impulse-driven, fast processes that require minimal cognitive analysis and effort (Evans and Stanovich, 2013). Also important are **social norms** which affect what the individual thinks is common practice and widely accepted (**descriptive norms**), and what ought to be done in society (**injunctive norms**). Here, studies in terrestrial environments have shown that people are more likely to litter if a) the setting is littered (descriptive norm) and/or b) if they witness someone litter (injunctive norm). Habits and social norms are important and may change as a result of legislation — as shown by the effect of mandatory charges on single-use carrier bags. This helps disrupt habitual behaviour by giving people a reason for change (the bag charge) and creating a new social norm (Poortinga *et al*., 2016).

while consumers blame manufacturers for not offering environmentally friendly products. Policy-makers are faced with the challenges of balancing these perspectives. The psychological foundation of this blame game is the well-documented phenomena of cognitive dissonance (Festinger, 1957), which suggests that people tend to adjust their thinking to justify their behaviour. Thus, if they contribute to plastic waste, they will prefer those arguments that prove that their waste production is inevitable or that their own contribution is insignificant compared with others' contributions (analogous to the 'tragedy of the commons' or the 'prisoner's dilemma'). Plastic waste pollution can be seen as a 'social trap' whereby nobody wants plastic waste *per se*, yet we still produce it, and try to explain our behaviours by blaming other stakeholders' behaviour.

Ultimately, however, consumers do have powers in market economies: if no one bought drinking water in plastic bottles, retailers would soon reallocate the redundant shelf space.

Against the background of these complexities, the evidence that consumers are likely to be influenced more by prices than behavioural measures is particularly relevant (DellaVigna and Pope, 2017). In this context, considerable success has been achieved in changing consumer behaviour by the simple measure of charging for plastic bags. More than 60 countries are already taxing or banning SUPs, primarily plastic bags (UNEP 2018a), and even small charges have led to reductions in use surpassing 90%[18] with associated reductions in litter. This has become a model of how to change

[18] For instance, the Irish Government introduced a levy of 15 cents per bag in 2002 raised to 22 cents in 2007), which had the effects of reducing bag use by 90%. The income from the levy is used to fund anti-litter initiatives, environmental research and development and initiatives by community groups on protecting the environment (Gitti *et al*., 2015). Plastic bag levies are now widespread (e.g. in England, a charge of 5 pence introduced in 2015 has reduced usage by 86%; https://www.gov.uk/government/publications/carrier-bag-charge-summary-of-data-in-england). Many countries have preferred to ban plastic bag use altogether (e.g. Brazil, China, South Africa, Uganda, Somalia, Rwanda, Botswana, Kenya and Ethiopia).

consumer behaviour and may also influence consumer attitudes. A recent analysis (Thomas *et al.*, 2019) of the effects of introducing plastic bag charges in the UK showed that the introducing the charge increased support for other charges to reduce plastic waste, so introducing one kind of pro-environmental charge could cause support to spill over to other policy options.

5.3 Market-based instruments

The plastic bag charge is one example of **market-based instruments (MBIs)** which use the price mechanism to make undesirable practices more expensive; while generating revenue that can be used to finance infrastructure or awareness-raising (Darnton, 2008). Various MBI options and necessary conditions for effectiveness were reviewed in Ten Brink *et al.* (2009) where the key principles involved include 'getting the price right' on the basis of 'full cost recovery' or the 'user pays principle'; ensuring that the price reflects the true cost of pollution on the 'polluter pays principle'; and that the charging mechanism provides an effective incentive for the desired behavioural change.

A second MBI is to use targeted deposit schemes on containers to reduce littering and boost recycling, and such DRS have already enabled many countries to achieve high collection rates for beverage containers (the five best performing Member States with deposit schemes for PET bottles (Germany, Denmark, Finland, the Netherlands and Estonia) reached an average collection rate for PET of 94% in 2014 (IEEP, 2017)). Reverse vending machines can provide an economic motive for return, as applied extensively in the German, Swedish, Norwegian and Lithuanian models (Box 8). The earning opportunity of deposits can also encourage retrieval of littered containers.

There is, however, debate over the cost-effectiveness of DRS schemes, typified by criticism of the proposed UK DRS scheme (IEA, 2019) that the anticipated improvements in recovery rate are insufficient to justify the high infrastructure and maintenance costs for reverse vending machines and reverse logistics. Several EU countries (including the Czech Republic, France, Ireland, Spain and Belgium) have concluded that the resource costs of introducing DRS outweigh potential environmental benefits. However, such economic cost–benefit analyses have difficulty in valuing intangible benefits such as reductions in litter as a result of a shift to returnable or refillable containers; this is further discussed in Chapter 8.

While most experience of DRS has been on bottled drinks, a Dutch study examined the costs and benefits of extending the deposit system from large PET bottles and refillable soft drinks and beer bottles, to include deposits on cans, smaller plastic bottles and one-way glass bottles (CE Delft, 2017). Such a DRS was calculated to reduce litter from cans and bottles by 70–90% and offer savings to litter bin clearance, litter clean-up costs as well as increasing the quantities of materials recycled and reducing GHG emissions. On the other hand, retail outlets would incur costs for installing reverse vending machines, additional staffing and transport costs which could be transferred to a higher consumer price. Limited experience has also been gained on encouraging reusable coffee cups through an MBI, where Poortinga and Whitaker (2018) found that a discount on reusable cups was less effective than a charge on disposable cups. Economic analysis of the costs of monitoring to prevent firms from disposing of collected low-value plastic wastes illicitly also suggests that deposit–refund schemes should also be considered for other low-value containers (Ino and Matsueda, 2019), since these may give rise to a recycling market.

5.4 Overall assessment of evidence

As shown earlier in Figure 5, many decisions and behaviours influence the scale of litter and its avoidance. For instance, a consumer may first buy a bottle of water instead of using a water fountain or their own bottle refilled from the tap; they then dispose of the bottle as general waste instead of reusing it or separating it for recycling; or may discard as litter. MBIs have been shown to influence behaviour at these various stages but other influences may be important. For instance, in studies on recycling and littering, Schultz *et al.* (2013) found that older people littered less, littering behaviour was less where bins were available and when the site was less littered. Halvorsen (2012) reviewed the effects of norms and policy incentives on recycling across 10 OECD countries and found that the strongest predictor of recycling efforts was the belief that it is beneficial for the environment, and to a lesser extent that it was a civic duty. Miafodzyeva and Brandt (2013) conducted a meta-analysis of 63 recent studies and found that moral norms, information and convenience were the most important predictors of recycling behaviour, followed by environmental concern.

Other studies reinforce that removing barriers should be the first step of any initiatives aimed at encouraging environmentally responsible behaviour such as waste selection or recycling (Bell *et al.*, 2001). If there are significant barriers for selecting plastic waste, no communication campaign can be expected to convince people to separate their waste. A communication campaign which tries to modify consumers' behaviour without removing barriers could even cause frustration and weaken environmental attitudes.

Such findings emphasise the need for a comprehensive approach on awareness information and on social norms to provide the framework within which MBI and other specific policy measures are applied. On the aspect of awareness, information on a product's sustainability

Box 8 Examples of DRS: Germany, Sweden, Norway and Lithuania

Of the various DRS operating in 38 countries, one of the most commonly cited is that in **Germany** which was introduced in 2002, against the opposition of the bottling industry and retailers. The German DRS covers plastic, aluminium, and glass containers for water, beer, soft drinks, and mixed alcoholic drinks. Excluded are containers for fruit and vegetable juice, milk products, wine, spirits, liquors, and certain dietary drinks, as well as containers smaller than 100 millilitres and larger than 3 litres. The deposit is 0.25 cents to retailers on single-use containers, and lower charges for refillable containers. Most (approximately 80%) of the collection is using reverse vending machines, and high return rates have been reported for PET bottles of 99%. This can be compared with the UK where there is no such DRS scheme where only 43% of the 13 billion plastic bottles sold each year are recycled, and 700,000 littered every day (EAC, 2017).

The original objective was to encourage drinks companies to use multi-use, refillable plastic or glass bottles (owing to the energy and GHG emission savings of multiple reuse). However, the proportion of multi-use bottles has declined and the remaining users are phasing out multi-use bottles in favour of one-time use, citing the high logistics costs of collecting bottles and providing storage space. The different charges for single-use and for refillable bottles have also caused problems with some stores limiting returns to containers purchased there. The exceptions for juice, milk, wine and spirits also add complications.

The German DRS scheme thus offers learning opportunities for other schemes. Firstly, despite the original objective being to incentivise multi-use of bottles, the financial reward of lower deposits for refillable containers has been insufficient to offset the costs of reverse logistics. Moreover, significant amounts of deposit are not reclaimed, leaving uncollected fees with retailers. These shortcomings suggest that larger incentives or a statutory duty to use only refillable containers would be required; and that consumers should be able to return containers to any store to avoid the inconvenience of having to return containers to the point of purchase (IEEP, 2017).

Sweden has applied a similar scheme since 2005 so that all packaging containing drinks (with the exception of drinks containing 50% or more of dairy products or vegetable fruit or berry juices) must be included in an approved return system. This has contributed to an 84.9% recycling rate in 2016 for aluminium cans and PET bottles, with a target to increase this to 90%. Return vending machines are available in most stores to make obtaining refunds simple. This scheme has, however, to deal with significant imports from other countries without deposits where the motive for recycling is reduced owing to the lack of deposit. Special campaigns have nevertheless offered small returns for charitable purposes and retrieved 35 million cans which were otherwise ineligible for refunds (see: http://pantamera.nu/om-oss/returpack-in-english/about-returpack/).

Norway achieves a high (97%) recycle rate for plastic bottles through a deposit scheme (13–30 cents) and has encouraged the concept of a container as a 'loan' where the default condition is that it be returned. Returning has been simplified and consumers can either use reverse vending machines or return it to shops and gas stations for cash or store credit. Implementing this concept has been supported by a conditional tax on plastic producers, which reduces according to the national recycle rate and is zero above 95%. Recycling has also been simplified by restricting manufacturers to using two PET resins, so that a recyclate quality is sufficient for closed-loop recycle to new PET bottles (https://infinitum.no). Such high rates of recycle contribute to Norway's low levels of plastic waste generated; this was the lowest found in a World Bank survey (Kaza *et al.*, 2018) at 26 grams per person per day (compared with France's 124, Germany's 226, the UK's 266 and the USA's 286).

While Norway, Sweden and Germany are often cited as leading examples of recycling, recent experience in **Lithuania** is also very positive. Lithuania introduced a new container deposit system in February 2016 with a container deposit of only €0.10 on glass and non-refillable plastic and metal beverage containers of between 0.1 and 3 litres in size. Despite the short time since its introduction, this DRS scheme has already increased the return rate for PET bottles from 34% before the scheme's introduction to 74.3% by the end of the first year and 91.9% by the end of 2017. Deposits are refunded when the empty container is returned for recycling; stores selling beverages must receive returned containers, so that return is easy for the consumer, and encourages additional customer visits.

The system is operated by a non-profit organisation established by the industry under the principle of EPR. The system operator is responsible for deposit clearing, reporting, logistics, marketing collected materials and educating stakeholders and consumers. Its sources of income include unredeemed deposits, revenue from the sale of collected materials and administration fees paid by beverage producers. Surveys showed that, by the end of 2016, 99.8% of the Lithuanian public were aware of the deposit system, with 89% having used it at least once; 58% of consumers reported recycling more and 78% believed the deposit system is good and necessary (see https://www.openaccessgovernment.org/recycling-lithuania-deposit-system-exceeds-all-expectations/45003/).

and recommended disposal methods on the label may contribute to appropriate disposal. However, consumers vary in the degree to which they have time or motivation to notice or respond to labelling. For campaigns differentiating between environmentally friendly and unfriendly behaviour, short project-based campaigns tend to have short-term effects so that to achieve significant and long-lasting effects there is a need for continuous, permanent communication efforts, using as many communication channels as possible in a coordinated way.

One final aspect raised by Zehner (2012) concerns whether the Jevons Paradox could apply in the case of plastics, as it has in the case of other efficiency-improving innovations[19]. In this case, making plastic

[19] This is named after William Stanley Jevons who in 1865 explained how James Watt's introduction of the steam engine greatly improved efficiency, which in turn made steam engines more popular and subsequently drove the use of coal ever higher.

products easier to collect and recycle could lead to an increase in plastic production and consumption. Issues of social justice also need to be considered if economic incentives are applied since these may have a disproportionately large impact on low-income groups while exerting little or no incentives to higher-income groups (Zehner, 2012).

In summary, a recent review of 187 studies (Heidbreder *et al*., 2019) observes that '*although problem awareness is high, the perceived advantages of plastic, consumer habits, and situational factors make it difficult for people to act accordingly. Bans and increased costs of plastic products as well as a combination of psychological interventions seem to be promising measures to reduce plastic consumption and waste. All actors from science, policy, industry, trade, and the general public have to work together to avoid a shift of responsibility. More research is needed to improve current interventions and to create additional powerful, immediate, and global solutions to limit the amount of plastic waste in the environment*.'

As noted above, consumers are just one (albeit a critically important one) of several stakeholders that influence the leakage of plastics into the environment, and should not be considered in isolation. Regulators and policy-makers need to take into account that the motives of the various stakeholders may not be in alignment; for instance:

- **Manufacturers** decide the materials and formats that are presented to the consumer. End-of-life considerations may be lacking or, on the other hand, influenced by considerations of reputation and corporate social responsibility. As legal entities, manufacturers (and retailers) behave more rationally than individuals whose behaviour is often determined by habits and emotions, so that economic and legal intervention is likely to be more effective if targeting companies (e.g. Dennis *et al*., 1990). In addition, regulatory intervention to increase the offering of products with lower environmental impact has immediate effect whereas awareness-raising to change consumer behaviour requires long-term efforts to achieve behavioural change in only a proportion of the population.

- **Retailers, especially food retailers,** can continue to rely on the convenient single-use model or they could choose to offer low-plastic options for products and services, support customers who want to use refillable containers, and provide collection and recycle infrastructure.

- **Citizens, environmental organisations** and **scientists** may collaborate on citizen science projects, beach clean-ups and similar community projects[20], or social media campaigns: for example, the 'Beat the Microbead' campaign (http://www.beatthemicrobead.org/).

- **Educational systems and educators** can offer curriculum material and innovative educational solutions, aiming to improve the pro-environmental behaviour of the younger generation and involve them in the development of a plastic waste free society[21].

Regulatory strategies will be more effective where the interests and motivations of different actors are aligned; this is addressed further in Chapter 8.

[20] An example of a holistic community project that involves non-governmental organisations, universities, companies, advisors, citizens and politicians is in the 'Plastics free Roskilde Fjord' project in Denmark which identifies plastics sources and community actions (see https://www.energyglobe.info/denmark2018?cl=en&id=280058)
[21] See, for example, the plastic-free schools initiative; https://www.plasticpollutioncoalition.org/guides-schools.

6 'Bio' plastics and degradability

The negative environmental impacts of plastics have led to efforts to find materials that have (or appear to have) more environmentally benign properties in their production or if leaked into the environment. Terms such as 'bioplastics' or 'degradable plastics' are widely used but can be ambiguous, so it is important to be clear on what functions and aims are involved in such materials. There are primarily three categories.

1. Bio-based plastics are where fossil fuel feedstocks have been replaced with biological materials (e.g. sugar, starch, cellulosic fibres, wheat, organic wastes). The primary objective for bio-based materials is to reduce GHG emissions relative to their fossil-fuel-based alternatives. These biological feedstocks can be used to produce the same polymer resins as fossil fuels (PET, PE, etc.), or entirely different polymers.
2. Degradable (or fragmentable) plastics are those that can break down in the environment into fragments through physical or chemical processes.
3. Biodegradable plastics can break down to environmentally benign residues through biological processes (generally involving bacteria) under various conditions encountered in the natural environment. Compostable plastics are designed to break down in industrial composting facilities or in the cooler and less-controlled conditions of 'home composting'.

6.1 Bio-based plastics

Bio-based plastics are currently produced using three approaches.

1. Use of natural polymers (e.g. starch-based plastics).
2. Polymerisation of bio-based monomers and oligomers via fermentation or conventional chemical processes (e.g. polylactic acid: PLA).
3. Polymers produced directly from bacterial fermentation. Polyhydroxyalkanoates (PHAs) are one examples; PHA functions as a source of energy and carbon in some (e.g. acetogenic) bacteria, and can account for up to 90% of the dry weight of the microbe. PHA can be produced directly by fermentation of waste (examples include paper mill wastewater (Tamis *et al.*, 2018) municipal wastewater (Korkakaki *et al.*, 2016; Pittman and Steinmetz, 2017) and waste polystyrene (Johnston *et al.*, 2018).

Bio-based plastics and their equivalent fossil-fuel-derived plastics are summarised in Table 4.

Where the plastic monomer normally derived from oil is produced instead from an agricultural or other 'renewable' source (e.g. PET made from corn or sugar), these are referred to as 'drop-ins' since they can easily substitute for the fossil-fuel-based monomer without the need to change equipment and production processes. However, where the biological feedstock produces a different resin (for instance, PLA, PHA), different additives and processing technology may be required, since there will be a different range of key properties. As an illustration of the range of factors that have to be optimised, Figure 6 shows the relative trade-offs in substituting PET or LDPE by PLA (a) or PBS (b) in terms of barrier properties, mechanical properties, recyclability and ease of processing versus the single advantage of biodegradability.

Global production of bio-based plastics is currently less than 1% of that of fossil-fuel-based plastics (approximately 2 million tonnes per annum). Considering their relative early development stage and lower production rates, it is inevitable that they are more expensive (e.g. bio-PE and bio-PP sell at approximately 30% premium, and PLA is about twice as expensive as PE). With process refinement and scale up, however, this difference is rapidly disappearing and the number of applications increasing. Research and development continue on expanding the range of feedstock options and polymers produced. Cellulosic fibres extracted from wood offer potential bio-based substitutes for some plastic packaging, or as up to 50% of the content of plastic composites[22]. A range of polyamides and

Table 4 Substitution possibilities by some 'bio-based' plastics (Chen and Patel, 2011; Gardini *et al.*, 2016)

'Bio-based' plastic type	Fossil fuel plastic substituted
Polylactides: PLA; inc. Polyhydroxy butyrate: PHB	PE, PP, PS
Polyhydroxyalkanoate: PHA	PE, PVC, PP, PET, PS
Polyethylenefuranoate: PEF	PET
Starch-based	PE, PVC, PP, PS
Cellulosic fibres	Wood-plastic composites, nanocellulose coatings
Polybutylene succinate: PBS	PE
Plant-oil-based polyamides	Polyamides (nylons)

[22] See 'The Wood Fibre Solution to the world's Plastic Problem' at https://eureka.eu.com/innovation/wood-fibre-plastic/.

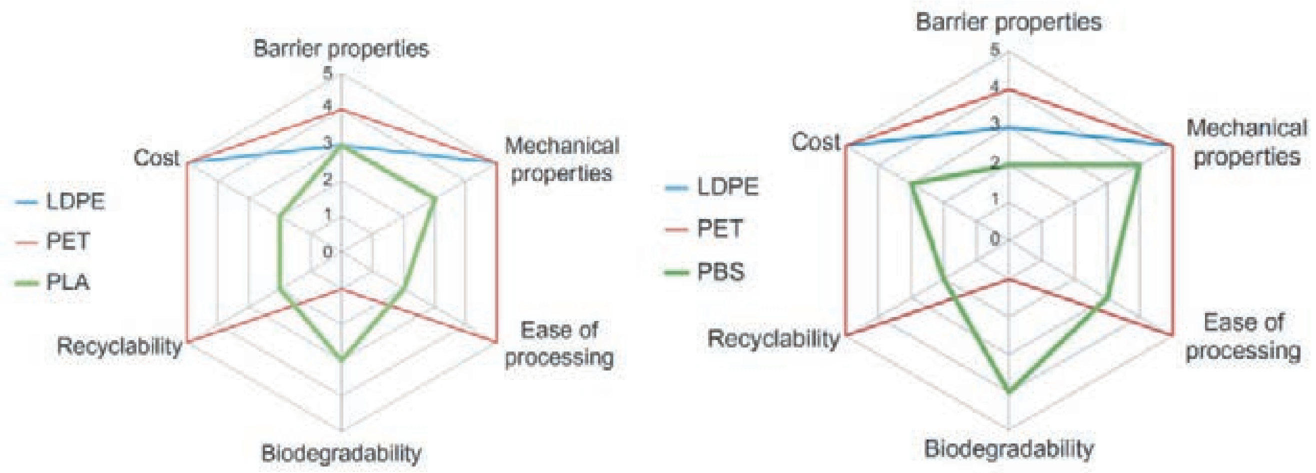


Figure 6 Trade-offs in substituting PET or LDPE by (a) PLA and (b) PBS (source: Bucknell, 2019).

polyurethanes can also be produced from plant oils (e.g. castor oil, sunflower oil) although the chemistry is complex (Maier, 2019). Novel feedstocks under research include keratin (e.g. from chicken feathers) (Werland and Brandelli, 2005; Khosa and Ullah, 2013; Scarfato *et al.*, 2015). Another source could be chitin whose natural production is second only to cellulose. This can be a source of chitin nanofibres (Wu *et al.*, 2014), and can be sprayed on to other materials to provide a barrier to oxygen for food, electronics and pharmaceutical packaging (Satam *et al.*, 2018). Furthermore, carbon dioxide is a potential carbon source for plastics (e.g. Dahrensbourg, 2007; Klankermayer *et al.*, 2016; Zhu *et al.*, 2016). This last example includes some commercial processes: Newlight's AirCarbon technology can convert methane to PHA, or carbon dioxide to polyurethane and thermoplastics.

The label of 'bio' has been used by some companies as an indication of lower environmental impact, but assessing whether overall environmental impacts are positive or negative requires full LCAs. For instance, in assessing life cycle GHG emissions, Nova Institute (2017) calculated GHG emission reductions of around 27% (relative to fossil fuels) in producing PLA, while Shen *et al*. (2011) calculated that producing PET bottles from bioplastic emits on average 25% fewer GHGs than if based on petroleum. Comparing fossil and bio-based PET bottles, Chen *et al.*, (2016) suggested a potential reduction in global warming potential of 21% when using woody biomass relative to fossil fuels. Such calculations can, however, underestimate the benefits of bio-based products based on crop wastes if the assessments include emissions from the primary crop production.

The primary motivation for making bio-based plastics is to reduce GHG emissions by using resources that are renewable and do not compete with food production or incentivise further land use change resulting in deforestation, loss of biodiversity and other factors (Sheldon, 2018). In principle, the global production of lignocellulosic waste is enough to serve as a raw material for the global production of plastics (Tuck *et al.*, 2012). However, industrial processes can also use agricultural products (e.g. corn, wheat) where such conflicts can emerge. For instance, to replace PET, PP or PE by the biopolymers PLA or PBS would require from 15.9 to 19.5% of current global wheat production and replacing PE by a bio-PE would require almost all (93.5%) of global wheat production (Bucknell, 2019).

The choice of the feedstock and avoiding such conflicts is thus the fundamental issue with bio-based plastics. Biomass used to make bio-based plastics should not compete, directly or indirectly, with food production, and should consist of unavoidable waste biomass, such as agricultural and forestry residues of lignocellulose and food supply chain waste. However, use for plastics competes with the use of the same wastes for renewable energy which are supported under the Renewable Energy Directive (EASAC, 2017c, 2019).

6.2 Physical breakdown and fragmentation

Plastics can be made to break down as a result of exposure to sunlight or oxygen by including special additives (e.g. metal elements such as cobalt, manganese, iron or zinc) that catalyse cleavage in the molecule chains on exposure to air and ultraviolet light; this chain breakdown results in small fragments. Such plastics are called oxo-degradable or PAC (pro-oxidant additive containing) plastic. As noted by Prasun *et al.* (2011) and Thomas *et al.* (2012), polyethylene containing pro-oxidants disintegrates on exposure to heat, light, and oxygen into small fragments, thereby reducing their visibility, but the fragments do not further biodegrade into nutrients that can be used in natural processes; moreover the additives will have deleterious effects on recyclate quality if included with other plastics. The European Commission reported to the Parliament that oxo-degradable plastics are not a solution to the environment problems of plastic leakage and that they are not suitable for long-term use, recycling or composting and has consequently included a ban on *all* oxo-degradable plastics in its SUP Directive (EC, 2019).

6.3 Biodegradable or compostable plastics

The most environmentally benign plastic would be a material that can break down through biological processes under a range of conditions to organic molecules and nutrients which can return to the natural environment (Shah *et al.*, 2008). Potentially, such plastics can be produced either from crude oil or renewable resources (see examples in Figure 7) and there is no general rule that 'bio'-based materials are more degradable or compostable than those derived from fossil fuels (Adhikari *et al.*, 2016); some may exhibit some degree of biodegradability while others may not be biodegradable at all. Biodegradable plastics have been extensively researched since the early 1980s with agricultural mulches a prime marketing target, since the large amounts of PE used in mulches and silage bales are difficult and expensive to collect and recycle and persist in the soil, interfering with cultivation and harvesting. Several polyester plastics are available for mulching (PHA, PHB and PBS among others) as well as starch-based films, and have been tested on large-scale applications. Biodegradable films are now available that can be ploughed in and subsequently degrade in the soil through the action of humidity and microorganisms, although costs per hectare of biodegradable materials are higher than PE film (for mulches in Spain, between 25% and 188% more expensive (Mari *et al.*, 2019)). A general claim of biodegradability is unlikely to be valid if not accompanied by details of the conditions required; indeed, special conditions are often required such as anaerobic digesters or industrial composting (Albertsson and Hakkarainen, 2017).

Using compost as a microbial community for the biodegradation of different bioplastics has been extensively studied in recent years. PLA, PHA, starch-based plastics, PBS, PES and PCL are susceptible to biodegradation by compost under specific conditions of temperature, pH and moisture content, but the specific conditions must be defined, as their effect on plastics degradation (especially for PLA and PHB) is significant (Castro-Aguirre *et al.*, 2017). In addition, over the timescale of organic recycling processes (composting and anaerobic digestion), most of the plastics biodegrade to only a limited extent, while some generate methane (Gómez and Michel, 2013) in the process. In general consumer use, PLA, starch-based and cellulosic fibre-based materials can be used for compostable packaging but their environmental degradability will depend not just on the environmental conditions but also on the additives that have been added in processing; these may even prevent degradation (Lambert and Wagner, 2017).

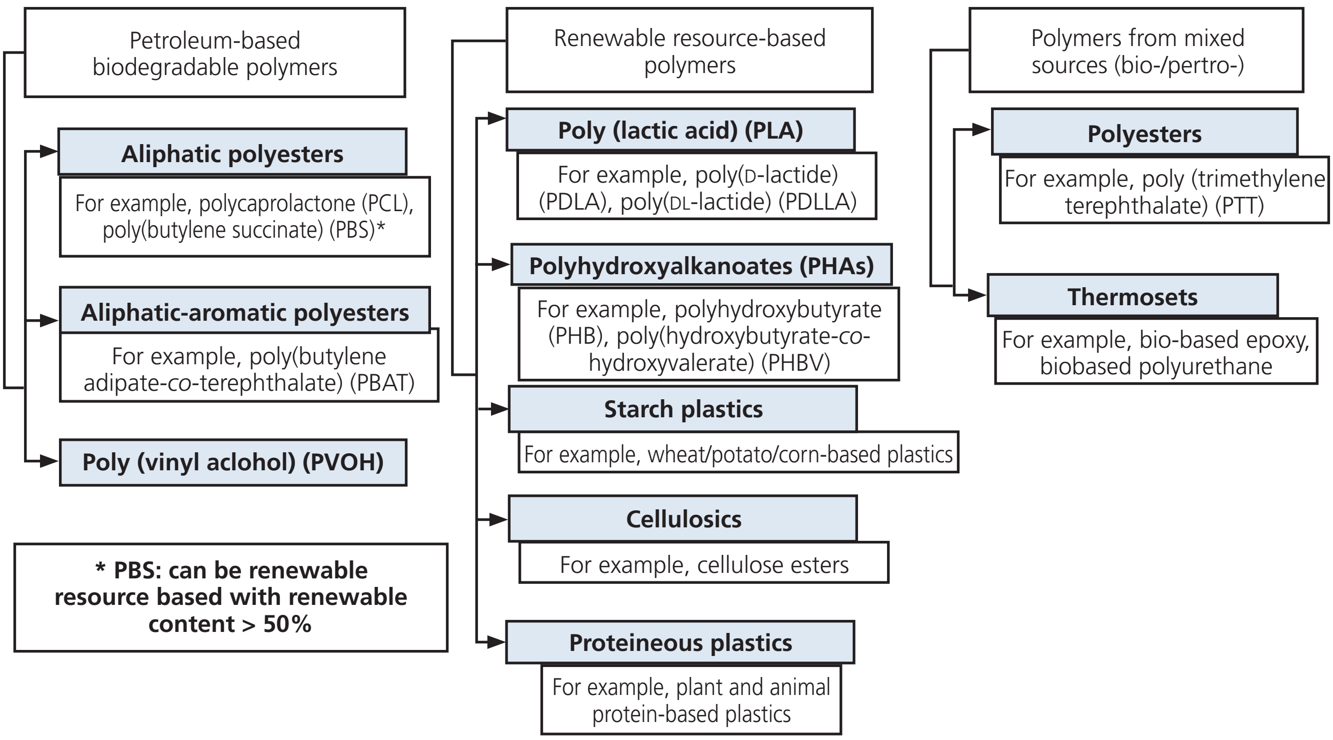


Figure 7 Biodegradable polymers (Reddy et al., 2013).

Various eco-labelling standards around the world define **home and industrial composting** and the time in which a plastic must degrade, although there are still questions over the reproducibility of such tests (Castro-Aguirre *et al.*, 2017) and additional work to develop and refine appropriate standards is thus required. Industrial composting generally involves temperatures above 50°C for weeks or months (UNEP, 2015). Industrially compostable materials are, however, not necessarily capable of being composted under the cooler and less-controlled conditions of home composting. Moreover, even when compostable, materials may not degrade in natural environments. Compostable packaging also interferes with plastic packaging recycling owing to their chemical structure and, if not separated, their large-scale production could seriously interfere with plastic recycling processes. As with the label 'bio', the appeal to the 'green consumer' of the label 'compostable' may not be based on sound environmental principles and could also lead to increased littering if consumers believe they will 'disappear' in the natural environment. Proper labelling and certainty in their end-of-life composting under appropriate conditions are thus pre-conditions for achieving environmental benefits; for instance, compostable containers could be required as part of food waste composting processes[23].

The ideal target of a plastic that breaks down naturally in the marine environment remains elusive. Fully degradable polymers are routinely used in biomedical applications where the temperature and humidity of the human body provide stable conditions for degradation. However, most applications of plastics require durability, and it is a basic premise that a material that can degrade in the environment should not degrade during its shelf life. Natural environments vary in temperature, humidity, degrading microorganisms and many other factors, so that degradation is much more difficult to engineer into the plastic molecule (Albertsson and Hakkarainen, 2017). In consequence, most fossil-fuel-based plastics do not biodegrade and even those that exhibit some degree of biodegradability are slow to degrade in marine and terrestrial environments, resulting in lifetimes of decades or even centuries (Krueger *et al*., 2015). Nevertheless, some progress towards biodegradability has been made and there are standards that allow such a product to be labelled as marine biodegradable, although Harrison *et al.* (2018) consider such standards as insufficient to realistically predict biodegradability in marine environments. The JRC and Vincotte both can test and award a certificate for products that reach 20% biodegradation in a marine test within a period of 6 months, and at least 70% disintegration (i.e. smaller than 2 mm) in a marine environment within 3 months.

The JRC has approved two grades of the Mater-Bi (a thermoplastic starch with PLA from Novamont) for marine biodegradation. The biodegradability of PHA can be refined through variations in molecular structure to make biodegradable packaging (Ghosh *et al*., 2019), and has been approved by Vincotte for marine degradability. There are over 80 different molecular structures within the polyhydroxyalkanoates (PHAs)[24] exhibiting different degrees of biodegradability (Chanprateep, 2010; Bagheri *et al.*, 2017). Some of these (PHB and PHBV) show some biodegradation in marine environments over 6 months (Deroine *et al.*, 2015; Jacquin *et al.*, 2019), but the degree of degradation may be quite low (Bagheri *et al.* (2017) found that PHB after 1 year had lost only 6% of its original mass, while PLA remained unchanged). Thus, if even such 'compliant' materials leak into the marine environment, they would still maintain their integrity for months with associated negative effects of entanglement, ingestion and other effects (Annex 2). Moreover, difficulties remain in processing and reproducibility, further limiting their potential to replace traditional plastics on a large scale.

Research continues; for instance, Ghosh *et al.* (2019) developed a bacterial process that produces monomer for PHA from seaweed; while another bacterium can convert PET plastic into PHA plastic. Several naturally occurring bacteria and fungi can degrade some plastics (particularly PHB, PLA and to a lesser extent PS) suggesting some scope for bioremediation (Caruso, 2015). Yoshida *et al.* (2016) found that bacteria (*Ideonella sakaiensis)* from a bottle recycling plant could digest PET by secreting an enzyme (PETase); this finding has stimulated work to improve the degradation process (Austin *et al.*, 2018) and further bacterial enzymes capable of dissolving PET in industrial processes at 60–70°C are under development (Wei *et al.*, 2016; Danso *et al.*, 2018; Kauertz ifeu[25]). Research and development is thus making some progress, but has not yet developed an environmentally benign plastic packaging for large-scale use that combines rapid degradation into naturally recyclable components with the necessary functionality and cost-effectiveness.

[23] For instance, in Italy residents are provided with kitchen caddies lined with compostable bags and bins that are emptied as part of door-to-door collections of food waste.
[24] 32,000 tonnes of PHAs were produced in 2013 (Aeschelmann and Carus, 2015) but the growth rate is high.
[25] https://www.ifeu.de/en/topics/biomass-and-food/biobased-materials/bioplastics/ and https://www.bioengineering.dtu.dk/english/news/nyhed?id=AFA835A7-EB08-4F05-A5EE-9212464DCF26

6.4 Overall situation

LCAs of replacing oil with agricultural crops show that 'bio' feedstocks are *not* inherently more environmentally friendly than fossil fuels, which is the presumption projected in marketing 'bio' products. The key question is the source of the raw material used with a high preference for using waste materials. The ambiguity of some terms (degradability, compostable, bio-based, etc.) can convey a misleading impression to many consumers of environmentally benign properties, whereas in reality they may be degradable only under special conditions not encountered in the natural environment; they may merely break down into smaller particles, as well as interfering with recycling processes. Such confusion may lead to cross-contamination of waste streams or careless or irresponsible littering based on a mistaken assumption that littered material will disappear from the environment.

Nevertheless, some progress in developing biodegradable plastics has been reported and further development is expected. Future development of bio-based or biodegradable plastics should be evaluated according to the following criteria (Maier *et al.*, 2018):

- their contribution to multiple use or the recovery of materials;
- the extent and rate of their 'degradability' in different parts of the natural environmental;
- certification should be on not just the basic resin but also include the properties of additives;
- labelling should be clear on the correct disposal route.

7 Research and innovation

There are many potential technical approaches and a full analysis of these is beyond the scope of this document. Furthermore, there is still considerable potential for more basic research (whether in universities, research institutions or industry) to address data inadequacies on environmental impact and to identify potentially more environmentally benign resins or formulations; for example:

- the fate of plastic debris in continental soil and soil-living organisms;
- the fate of plastics in the open ocean (surface, water column, sediments);
- health effect of plastic debris and nanoplastics on living organisms;
- design of new products for reuse or recycling;
- enhancing the degradability of plastics and developing plastics that degrade swiftly through natural processes;
- improving chemical recycling to achieve full de-polymerisation.

Research needs in some of the above fields have been analysed (e.g. in Vegter *et al.* 2014; Horton *et al.* 2017), and some of the various major technical and innovation challenges are provided in Table 5.

The wide range of approaches being pursued by various companies' research and development can be seen from the limited examples in Box 9. Furthermore, shopping and consumption patterns are already changing with different potential refill options (e.g. Lofthouse *et al.*, 2009). Another approach is to remove or reduce the need for recycling altogether by continuing to use plastic items but implementing a closed-loop system. This is the approach taken in the trial of a new 'loop'[26] scheme of refillable and returnable containers whereby customers order products that normally come in single-use plastic packaging. The products are delivered in durable, refillable containers that can be collected from the doorstep and cleaned for reuse.

Table 5 Some research and innovation targets (adapted from EMF (2016))

Innovation field	Description	Current state
Remove additives	Separation of additives from recovered polymers to increase purity of recyclate	Laboratory stage; limited application
Reversible adhesives	These would allow multi-material packaging to be separated into separate recycling streams	Research stage, but potential in making multilayer films from compatible polymers, removing the need for this
Depolymerisation	Returning the plastic to its original monomer	Processes are under development but costs are a barrier to large-scale use
Chemical markers	To facilitate separation by automatic sorting technologies	Markers available but not yet deployed at commercial scale
Near infrared	Automated optical sorting based on the different NIR spectra of different polymers	Now widely deployed at commercial scale
Biodegradable plastics	Plastics that will break down to environmentally benign residues in marine, freshwater or terrestrial environments	Still very limited to specific conditions (e.g. industrial composting): see section 6.3

[26] www.loop.com

Box 9 Examples of innovation to improve circularity of the plastics economy

1 Innovation in areas such as material design, separation technology, reprocessing technology. For example:
- Mono-material packaging containers can improve recyclability (e.g. https://corporate.dow.com/en-us/news/press-releases/dow-launches-game-changing-fully-recyclable-polyethylene-packaging-solution-in-india).
- Multi-material film packaging which is difficult to recycle can be replaced with a mono-material laminate based entirely on PE, and which can thus be recycled to other PE film products (www.borealisgroup.com).
- Process for depolymerising PET that takes place at relatively low temperatures (e.g. http://www.ioniqa.com/pet-recycling/).
- Producing plastics from captured greenhouse gases carbon dioxide or methane (e.g. https://www.newlight.com/).
- Closed-loop chemical recycling for Nylon 6 via depolymerising to caprolactam (e.g. https://www.aquafil.com/newsmedia/how-facility-will-recover-nylon-6-from-carpet/).

2 Improving recycling technology and systems
- Mechanical sorting combining various techniques (flotation, screens, magnets, manual sorting) for dry fractions such as metals, glass, paper, and plastics.
- Optical sorting technology recognises polymer types by illuminating the material and analysing the reflection spectrum. Image recognition could recognise specific packaging items.
- Marker technology such as machine-readable fluorescent inks and sorting technologies to improve polymer identification (e.g. http://www.wrap.org.uk/sites/files/wrap/Optimising_the_use_of_machine_readable_inks_for_food_packaging_sorting.pdf).
- Pyrolysis and chemical processes (as mentioned in section 4.1).
- A recycling robot equipped with artificial intelligence that can identify and separate materials faster. Algorithms enable it to detect packaging details such as logos and images — and then recognise them for sorting.
- Means of using combined PE and PP which together account for two-thirds of waste packaging.
- New technologies to remove colour, odour, and other contaminants from post-use polypropylene (e.g. https://purecycletech.com/).
- Converting polystyrene to styrene monomer which can be repolymerised (e.g. https://www.agilyx.com).
- Bacterial processes can turn non-degradable plastic into PHA (e.g. http://www.bioplastech.eu/).
- Solvents that can separate the tightly laminated layers of composite materials.
- Using a catalyst to breaks open a polymer chain to trigger a chain reaction leading to a range of organic acids which can be used in other chemical processes (e.g. https://www.biocellection.com/).
- Use of a catalyst in PE and PP that does not interfere with the recycling process but, after a predetermined time, breaks down the polymer chains to lengths that are degradable (e.g. www.polymateria.com).
- Feedstock recycling process to take mixed waste and generate a low-sulfur fuel oil (e.g. https://recyclingtechnologies.co.uk per tonnechnology/plaxx/; www.neste.com).
- Proposals for a process to convert LDPE plastic bags into a recycled LDPE product (https://repository.upenn.edu/cgi/viewcontent.cgi?article=1115&context=cbe_sdr).

8 Policy implications

In the previous chapters we have noted that plastic packaging has become an integral part of the supply chain in the production of goods to the consumer, and offers many desirable properties: durability, lightness, flexibility, hygiene and security from tampering as well as freedoms for the designers in terms of shape, colour and texture. While, superficially, packaging may appear to be just a container or marketing platform, it is likely to have been selected specifically to protect and preserve its contents (against bacterial contamination, exposure to oxygen, leakage of liquids or gases, damage from transport, etc.). Even for mundane applications, packaging films and containers have to meet strict demands concerning permeability of gases and liquids, or resistance to sterilisation. In many applications, only sophisticated polymers, multilayer or composite materials can meet the application's demand, and sophisticated compromises have been found to deliver economically the required films and containers.

Exploiting the many beneficial properties of plastics has resulted in rapid growth in production, and plastics manufacturers are planning for continued growth by substantial investments across the world[27]. In parallel with this growth, however, increased awareness and concerns over contamination of the environment in general and the damaging effects on marine organisms in particular (Annex 2) have led to a range of initiatives to reduce leakage into the environment and shift to a less linear economic model (section 2.1). These include the actions in the EU which are summarised in section 2.3, and which are affected by several science and technology-related aspects discussed in Chapters 3–7. In this final section, the Expert Group discusses the implications for achieving the current objectives of EU policy, the objectives of which it broadly supports.

8.1 The scale of the challenge

This study was launched to support the EU's policy development in its plastic strategy announced in early 2018 (Chapter 2). That analysis identified structural deficiencies in the current linear model and saw increasing recycling as a primary objective, noting that only 9% of plastic was currently recycled. That challenge has become even greater as the deficiencies in the existing plastic 'recycle' system have become clearer as a result of China's decision to cease accepting imports of plastic waste from the end of 2017. This has had major repercussions at both global and local levels (see Box 10).

As pointed out in Chapter 2, EU Member States had relied on exporting their plastic waste for most of their 'recycling'. This offered the lowest short-term costs but also created opportunities for financial gains to intermediaries who paid inadequate attention to the legality of the waste's treatment after export. Brooks *et al*. (2018) compiled trade statistics for the period 1988–2016 and found cumulative exports to total 26.7 million metric tonnes (MMT) from the USA, 22.2 MMT from Japan, 17.6 MMT from Germany, 10.5 MMT from Mexico, 9.26 MMT from the UK, 7.71 from the Netherlands, 7.55 MMT from France, and 6.41 MMT from Belgium. More recent studies (e.g. Greenpeace, 2019) have tracked the flows of plastic waste since the Chinese restrictions and found an immediate diversion of exports to Southeast Asia, in particular Malaysia, Vietnam and Thailand. In response to local mismanagement of the waste, import restrictions increased during 2018 which diverted waste to the next rank of unregulated countries- particularly India, Taiwan, South Korea, Turkey and Indonesia. A second wave of restrictions is now underway (e.g. India banned plastic waste imports from September 2019) which is strengthening demand to export to countries yet to announce restrictions on imports (e.g. current high-import-accepting Indonesia and Turkey) and a search for new countries to accept waste. Meanwhile the loss of the cheapest means of disposing of plastic waste has disrupted local collection economics, making it more costly to separately collect plastic waste since it must now be incinerated, landfilled or stockpiled until additional recycling capacity is available.

The Expert Group considers this historical reliance on exporting to countries that lack the proper infrastructure for dealing with their own waste is incompatible with the overarching objectives of sustainable development. Moreover, Jambeck *et al.* (2015) found that 16 of the top 20 countries contributing to marine plastic pollution were middle-income countries, where economic growth often outpaces the development of effective waste management infrastructure. Diverting waste previously handled by China to such countries is perverse when the policy objectives are to reduce such leakage. Ethical objections also exist to a practice where high-income countries are exporting waste to low- or middle-income countries without consideration of the subsequent impacts on the receiving country's environment or public health, particularly in the light of evidence on

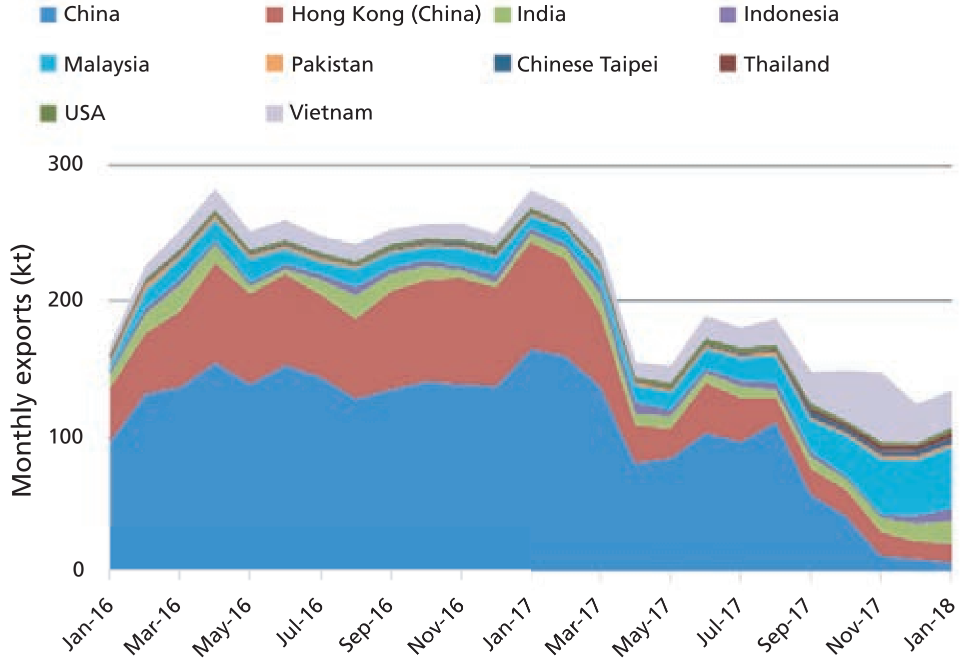
[27] Current investment plans are expected to increase production capacity for the monomers ethylene and propylene by 33–36% by 2025 (CIEL, 2017).

health risks not just to informal recyclers (e.g. Yang *et al.*, 2018) but (from media reports) on the adverse local environmental and health impacts of low-technology recycling, open-air burning and abandonment of mixed plastic waste from European Countries, North America and Japan[28]. Moreover, some investigations (e.g. NAO, 2018) show that little or no monitoring of exports has been conducted and any attempts to apply quality control to plastic waste exports is also undermined by the large proportion of waste plastics that are traded illegally (estimated at US$10 billion to $12 billion annually by ISWA (2014)).

The Expert Group thus recommends that the EU should support an effective ban on exports of plastic waste outside the EU independently of the amendments to the Basel Convention which will only enter into force in 2021. European plastics policy should be based on the presumption that waste produced within the EU will be handled within the EU. Exports once the revised Basel Convention has been implemented should only be allowed to be classified as recycled where the recycling capability and end uses of the plastic waste have been properly audited. As emphasised in Brooks *et al.* (2018), this will require waste-exporting countries to develop and expand internal recycling markets, and where these are insufficient, to reduce use and redesign plastic packaging and products so that they retain their value and are more recyclable in domestic markets. The Expert Group also notes that a significant proportion of plastic waste (27.3% in 2018) still goes to landfill, which should not be an acceptable alternative option for plastic waste no longer exported. A parallel objective of zero landfill should also be adopted.

Box 10 Effects of the Chinese restrictions of the import of plastic waste

Exporting to China had become the single largest route for 'recycling' plastic waste from the USA, Japan and many EU Member States (Brooks *et al.*, 2018) during the period 1988–2016. However, following China's 'National Sword' policy, imports of all but very pure plastic scraps were prohibited from late 2017 (Rico, 2018). The result was that exporting countries diverted their mixed plastic waste to other Asian countries; exports to Vietnam doubled, to Thailand by 15-fold, and to Malaysia by 3- to 4-fold (see Box Figure 10.1).



Source: Eurostat (2018), *Eurostat - Data Explorer - Generation of Waste*, http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=env_wasgen&lang=en (accessed on 28 March 2018). HS code 3915

Box Figure 10.1 Shifts in EU plastic waste exports from 2016 to 2018 straddling the Chinese restrictions on plastic waste imports.

Continues on next page

[28] See, for example,
https://www.theguardian.com/environment/2019/may/28/treated-like-trash-south-east-asia-vows-to-return-mountains-of-rubbish-from-west
https://www.bbc.co.uk/news/world-asia-46518747

Box 10 *(continued)*

Exporting plastic waste has grown owing to the lack of sufficient capacity to recycle in the countries producing the waste, and because these exports have been counted as 'recycling' and contribute to meeting national recycling targets. However, the countries now receiving wastes already had insufficient infrastructure to deal with their own plastic waste. As a result, the increased flows have led to local pollution and large quantities being dumped or abandoned (Box Figure 10.2). As the initial destinations introduced bans or restrictions, plastic waste exporters shifted to a second tier of countries lacking such restrictions, primarily Indonesia, Turkey, India and South Korea (Greenpeace, 2019). As large-scale imports have become more difficult, this has had an effect on total volumes shipped, which have reduced from 12.5 MMT in 2016 (from the top 21 exporting countries) to an annual rate of 6.4 MMT in 2018.

Box Figure 10.2 Plastic waste abandoned in Malaysia (30 January 2019; www.ban.org).

An additional factor is that awareness of the real fate of plastic waste diligently separated by EU consumers can be expected to have negative effects on motivation to support future plastic waste reduction efforts since, as we have noted in Chapter 4, this calls into question the efficacy of individual actions. Export statistics show the extent to which Europe, North America, Australasia and even parts of Central and South America and Africa have relied on exports for the removal of their plastic waste. The EU thus has the opportunity to take the global lead for high-income countries to put their own houses in order to adapt to a new reality where unregulated dumping on other countries is no longer an acceptable means of disposal.

8.2 Plastics within the circular economy

The EU plastics strategy is placed within the wider framework of the circular economy whose key characteristics were briefly introduced in Chapter 2 and Box 1. Fundamental principles underpinning the circular economy are to extract the maximum use from the natural resources consumed, to minimise waste and to ensure that the maximum value is extracted at each stage from the materials contained within the product. This has also been reflected in the EU's Waste Directive in terms of a 'waste hierarchy', where each stage in the hierarchy needs to be optimised before moving down to the next. As shown in Figure 8a, this starts with *prevention*, namely the need to minimise the use of materials and move their uses to a more cyclical pattern *before* considering end-of-life issues. Then, at the end-of-life stage, reuse is of higher priority than recycle, which is a higher priority than disposal. Penca (2018) adapted the basic hierarchy model to include litter and prevention approaches shown in Figure 8b.

The European Parliament emphasises that prevention of plastic waste should be the first priority (EP, 2018) and

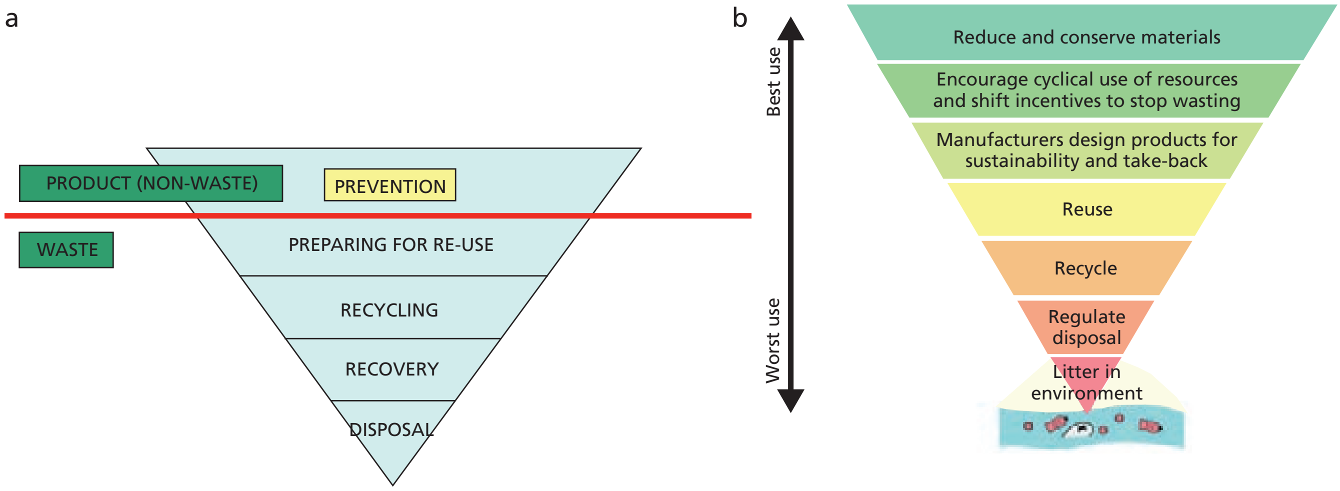


Figure 8 (a) Waste hierarchy in EC Waste Directive; (b) as adapted in Penca (2018).

other authors have pointed to reducing material use as the first stage in strategies to reduce marine litter (e.g. Ten Brink *et al.*, 2016; UN Environment, 2017; OECD, 2018b). Penca (2018) has commented that the EU's Plastics Strategy focuses primarily on the lower tiers shown in Figure 8 and has avoided any direct objective or targets for the higher levels of reducing overall material use in plastics, nor for special measures to prioritise reuse, while industry continues to invest under a scenario of continued growth in plastics production and use.

The inclusion in Article 4 of the SUP Directive (EC, 2019) that Member States should 'achieve an *ambitious and sustained reduction in the consumption of the single-use plastic products … leading to a substantial reversal of increasing consumption trends*' is thus to be welcomed, as are industry commitments to reduce unnecessary packaging (Box 5). As pointed out earlier, even improvements in recycle rate and short-term reductions in leakage will provide only a short-term slowing in environmental impact if consumption continues to grow. A sustainable solution needs to meet the needs of humankind within the limits of the planet, and is not compatible with continuously growing plastic use and its associated demands for oil and gas. A core precept of circularity is that it should reduce material flow: in other words, aim for REDUCED plastic manufacture which is the opposite of current investment trends. Within this overall reducing trend, policies should aim to eliminate leakage into the environment.

A specific aim to reduce usage as part of the broad strategy to reduce leakage is supported by evidence that reducing usage does reduce leakage. In Chapter 5, we pointed to experience that restrictions on plastic bags were followed by reductions in littering. Supporting evidence also comes from the most recent survey of plastic in rivers (Earthwatch Institute, 2019) which showed that bottles made up 14% of visible items of litter, and plastic bags only 1% (in tenth position behind food wrappers, cigarette butts, disposable food containers, cotton-bud sticks, takeaway cups, etc.). Plastic bags showed a substantial decrease compared with the 2015/16 survey performed by the JRC when bags constituted 7% of the litter and were in sixth position. Reduction in use (prevention) is thus likely to be associated with reduced leakage; as a consequence, continued high rates of growth in consumption appear incompatible with addressing the environmental damage associated with leakage. The role of prevention in the waste hierarchy is also recognised by OECD (2018b) with its emphasis on reducing unnecessary use (when technically feasible) and for plastic products to be designed to allow for reuse to minimise the amount of waste generated. STAP (2018) also emphasises that the first priority in addressing the environmental impact of packaging plastics is to discourage (*inter alia*) non-essential production and unnecessary consumption by eradicating excessive plastic packaging on products.

The Expert Group thus recommends that a reduction in material flow should be an explicit objective for all packaging plastics in the 'Plastics in the circular economy' package with priorities set by the '6Rs': reduce (raw material use); redesign (design products for reuse or recycling); remove (SUPs when practical); reuse (alternative uses or refurbishment); recycle (to avoid plastics going to waste); recover (extract chemicals or fuels, or incineration for energy production). The aim would be to keep resources in use for as long as possible, to extract the maximum value from them while in use, and to recover and regenerate products and materials at the end of their service life. 'Slowing the material loop' by reducing demand and discouraging non-essential production and use is particularly important since the role of substitution may be limited by the higher resource and energy demands of alternatives summarised in the next section.

8.3 Alternatives to plastic?

One question raised in policy debate is to what extent plastic packaging is essential and whether there are less environmentally damaging alternatives that may also be easier to recycle. However, given the wide range of options for designers to select a plastic formulation most suited to the goods it is covering, and the cheapness and lightness of the packaging, replacing plastics by other materials is not straightforward. Alternative materials may be heavier or bulkier (glass, metals), and their production may have resource implications (paper, metals) while lacking the flexibility and low cost of plastics. LCA studies indicate that there may be substantial penalties to substitution in terms of increased GHG emissions and other resource demands (Box 11).

Although substitution may be possible in specific (especially niche) markets and applications, it is not possible to argue that a general aim to replace current

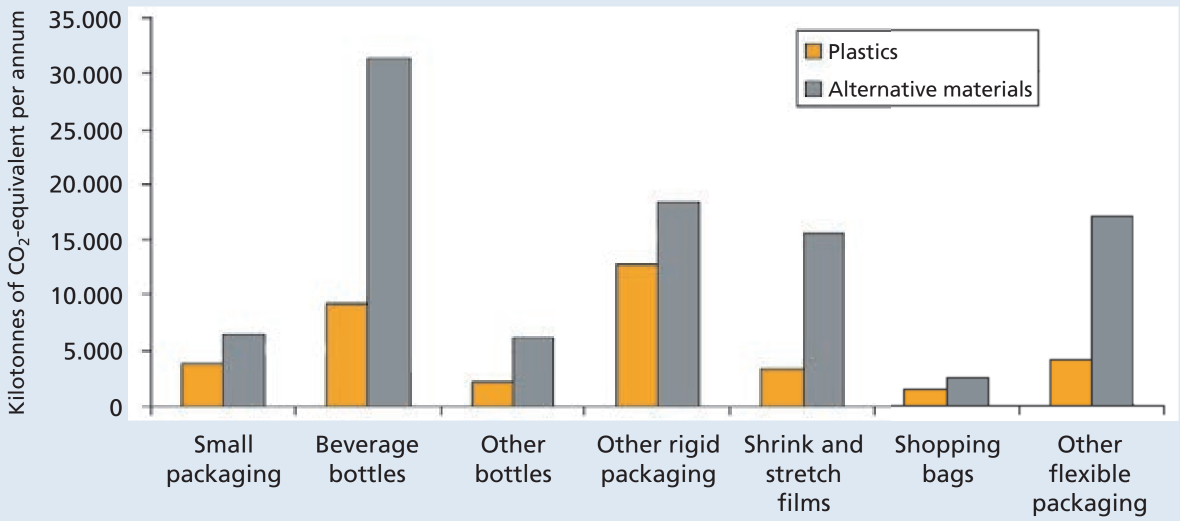
Box 11 Comparative evaluation of plastic and alternatives in packaging

An independent study commissioned by the plastics industry (Brandt and Pilz, 2011) evaluated the overall environmental impacts of substituting plastic packaging by other materials in seven types of packaging: small packaging, PET bottles, other bottles, other rigid packaging, shrink and stretch films, shopping bags and other flexible packaging. Fifty-seven products were examined where the polymers (LDPE, HDPE, PP, PVC, PS, EPS and PET) were replaced by tin plate and steel packaging, aluminium, glass, corrugated board, cardboard, paper and fibre cast, paper-based composites or wood. All plastic packaging types showed advantages compared with the mix of alternative materials, with beverage bottles, shrink and stretch films, and other flexible packaging showing the largest differences (see Box Figure 11.1).

This is because plastic packaging usually provides the same function with significantly less material, so that less energy is required in production. In addition, reduced weight and lower volume than substitutes reduce transport space and energy use. In packaging that preserves food, reduced food loss also reduces emissions. Similar results have been obtained by other authors. Galli and Vechellio (2004) compared energy balances for PET versus glass bottles and HDPE versus paper sacks, while an analysis for the American Chemical Council (ACC, 2018) showed that other environmental impacts were lower for plastics than the materials likely to substitute for them (water, solid waste, nutrient emissions and effects on the ozone layer).

In practice, manufacturers have to consider a multiplicity of factors in deciding containers as is illustrated by the choice between glass or PET for beer bottles. One analysis (https://www.packagingdigest.com/beverage-packaging/material-or) considers performance indicators within the three categories of price, environmental impact and performance, and shows how the advantages of glass or PET vary with each indicator. Assessing the relative merits of the two options thus requires a balance to be struck between different indicators and is sensitive to assumptions (e.g. on recycling rates).

Comprehensive analyses of life cycle environmental impacts of various options for replacing single-use LDPE shopping bags (Danish Environmental Protection Agency, 2018) have also demonstrated that replacements need to be used multiple times before any environmental benefit can be achieved relative to the base case of a single-use bag being used as a bin-liner and then incinerated. When all environmental indicators were considered, available alternatives to LDPE had to be reused from 35 to over 1000 times before their overall impact was lower than the base case. This did not, however, consider littering effects, which other studies have shown to decline as single-use bag usage is reduced.



Box Figure 11.1 Effects of substitution of plastic packaging on life cycle GHG emissions (Brandt and Pilz, 2011)

Box 12 Experiments in zero plastic shopping

'Zero-waste' or 'zero packaging' initiatives have been growing but generally on a small and local scale. Large volume retailers have been more hesitant, so an experiment just started in Oxford, UK, is interesting, since one supermarket is offering customers the chance to buy food and drink that is completely free of packaging. Hundreds of products have been removed from their packaging, and shoppers will be able to fill their own containers, with prices typically 15% cheaper than the packaged alternatives. This is a reversal on other supermarket charging policies where loose product prices often exceed packaged prices by substantial amounts. Related issues of hygiene, consumer reactions and security remain to be clarified through such experiments.

Source: https://www.waitrose.com/ecom/shop/featured/groceries/unpacked.

Figure 9 An example of the limited choice offered to consumers between packaged and loose fruit and vegetables.

plastic uses with other materials will offer environmental benefits. This leads to the next question of whether the anticipated continued growth in plastics production is justified — in other words, are the projected uses in packaging necessary or are they a material seeking new uses because of the increased production of polymer feedstock? Public concerns over what is seen as 'over-packaging' have led to calls for a plastic-packaging-free supply chain (see, for example, 'zero waste shops' at https://thezerowaster.com/zero-waste-near-you) and some supermarket trials (Box 12). However, switching to such zero packaging options requires consumers to make deliberate choices, generally involving additional time and costs relative to purchasing at major retail outlets such as supermarkets. EU regulations should avoid impeding such initiatives, but the main priority remains to reform the current supply chain, where EPR is a critical tool identified by both the European Commission (EC, 2018a, 2018b) and reinforced by OECD (2018b).

8.4 The role of extended producer responsibility

Manufacturers consider several factors when deciding what and how much packaging to use, taking into account the contents, packing for transport, storage at the point of sale, protection against loss and damage, speed of processing at check-out as well as attractiveness to the consumer. What happens at the end-of-life is thus just one of several critical operational decisions and the evidence is (as in Chapter 2) that historically this has not been seen as a priority in selecting packaging composition and design. This may result in severely limiting the choices facing the consumer, as illustrated in Figure 9.

In the light of the high public concerns over pollution by plastics, the response of retailers in the absence of additional regulation is of interest. Here, recent surveys of plans by UK supermarkets (EIA, 2019a) show no strong trend to reduce dependency on SUPs. Only one company has committed to eliminate its own brand single-use plastic packaging (by 2025), while some others are expanding their loose produce ranges and refillable options, or phasing out difficult-to-recycle formats (PVC, PS, etc.). However, others have no such plans and are even seeing an increase in plastic used for packaging. Meanwhile, disincentives remain owing to significantly higher prices charged by some supermarkets for loose products. This survey also showed that retailers are not seeking to influence their supply chain, while some have chosen policies (e.g. compostable bags) that may interfere with the recycling system (Chapter 6). An update (EIA, 2019b) showed that plastics use was still increasing overall, and that consumer behaviour has started to adapt to the availability of low-cost reusable 'bags-for-life'. Sales of these had risen to 1.5 billlion in 2019 (75% of the number of single-use bags given away in 2016), suggesting that many consumers are treating them in the same way as single-use bags. Since reusable bags must be used over four times to deliver a net environment benefit, the initial resource and GHG savings following the single-use charge have now been more than offset, leading to calls for much higher charges.

Judgements on whether or not to use plastic packaging are complex and often involve trade-offs (e.g. between packaging and shelf life; between wrapping and bruising). Regulators cannot second-guess manufacturers' choices but they can use the EPR system to incentivise industry to give more consideration to the end-of-life handling of their packaging. The Expert Group concurs with the European Commission's view that EPR is an important tool for addressing some of the market failures in the current system (Chapter 3) but emphasises that charges must be sufficient to ensure that end-of-life recycling is considered from the design stage through production and use, so as to minimise material flows and maximise value recovery through recycling. The question arises therefore what would be an appropriate charge, and on what basis should it be assessed.

Existing EPR charges in Member States range widely, with the highest being Austria and Italy at €200 and €253 per tonne of packaging used. Objective valuation of environmental externalities is notoriously difficult and consensus among economists elusive. However, UNEP (2014) estimated the externality cost[29] of plastic packaging in the consumer goods sector to be US$75 billion per annum which, if expressed as a fraction of the global packaging market (approximately US$800 billion), would be about10% of the costs of packaging, which is approximately the same as the Austrian and Italian average charges[30]. This could thus provide a minimum baseline for the overall charges to be levied through EPR, although more research is required on appropriate charges and the effects of different types of EPR scheme.

A second issue relates to the objectives and detailed designs of EPR schemes. In Chapter 3, we listed possible objectives and consider that optimising recycling possibilities and reducing to a minimum (compatible with commercial, health and safety objectives) the use of packaging were primary objectives. To achieve this, individual and eco-modulated schemes would be preferred. The Italian scheme, which involves significant eco-modulation, was described, but the French system also includes some degree of eco-modulation and the new Dutch and German Packaging Laws (from 1 January 2019) not only aim to achieve an increase in recycling rates, but also reward those who use packaging that is easily recyclable or made from renewable raw materials.

The Expert Group recommends that the Commission should adopt objectives for EPR schemes to do the following.

- Create an incentive to reduce the amounts of packaging used and encourage reuse.
- Maximise recyclability of end-of-life packaging.
- Minimise the proportion of packaging that is unable to be recycled.
- Integrate with availability of recycling infrastructure (e.g. by using proceeds to improve local recycle infrastructure).
- Apply to *all* packaging (including imported goods and packaging in products purchased via the Internet which tend to use more packaging than when buying goods in a store).
- Aim to eliminate cost burdens on local governments from plastics disposal.
- Ensure the EPR scheme is formulated in such a way so as to support recycling within the EU and to disallow export to lower cost and environmentally damaging alternatives.
- Ensure that the EPR exerts its effects across the whole value chain and is not just absorbed by the producers of packaged goods thus negating its influence upstream (e.g. plastic resin producers) and downstream (e.g. retailers and consumers).

8.5 Deposit return schemes

Many countries have found DRS to be a very effective means of increasing return rates for containers (Chapter 5) with an associated reduction in littering. Recent introduction of a DRS in Lithuania has shown

[29] The Natural Capital Cost includes costs arising from GHG emissions, and cost of air, water and land pollution from inadequate waste management and littering.
[30] Assuming a price for packaging raw material of €1.9 per kilogram.

substantial increases in recovery rates within a year of the scheme's introduction. Nevertheless, the high costs of installation have persuaded some EU Member States to seek to improve kerbside collections rather than deploy DRS. The Expert Group considers, however, that enhanced kerbside collections are unlikely to achieve the very high return rates achieved in DRS-applying countries and will be less effective in reducing littering. Moreover, economic assessments that conclude that DRS is not cost-effective may not have fully considered the benefits from reduced littering and reducing overall environmental plastics contamination. The Expert Group thus supports the wider deployment of DRS in Member States, and considers that such schemes should also be considered for application to cans, all plastic bottles and other recyclable containers. This is particularly important given the current excess of PET recycling capacity within the EU[31] and additional demands are anticipated for PET bottle- bottle recycling commitments by some major beverage manufacturers.

Previous objectives for some DRS included encouraging refillable containers, but experience so far has been that incentives have been insufficient to overcome the reverse logistical and other obstacles to container collection, cleaning and reuse. As a result, the use of refillable containers has continued to decline. Life cycle analyses comparing one-way containers with multiple reuse systems show that the point at which refillable containers achieve significant resource and energy savings depends on the specific circumstances of the individual product, packaging format, supply chain and logistics, especially the distances involved in containers' return (WRAP, 2010). The additional requirements for refillable containers (e.g. thicker bottles, vulnerability to high temperature cleaning and sterilisation as well as the reverse logistics) thus need to be balanced against the resource savings taking into account consumer behaviour. The European Commission could consider whether guidance could be provided to Member States on conducting such assessments.

8.6 Improving recycling

The Expert Group discussed in Chapter 4 the technical barriers to recycling and how these may be overcome, noting that strategies will be more effective where the interests and motivations of different actors are aligned. On organisational aspects, EPR and DRS may improve the supply of plastics to the recycling process but barriers still exist to developing economically sustainable processes.

The disruption described above following the Chinese import restrictions emphasises the fundamentally poor economics of recycling plastics. Outside highly selective and well-separated container recycle streams (e.g. PET bottles), mixed packaging plastics are difficult to recycle, involve costs that are often higher than the price of virgin materials, and face quality challenges that are difficult to overcome. This is a fundamental problem arising from the inherent complexity of the different plastic uses which involve very sophisticated manipulation of the molecular structure of the resin combined with choice and refinement of additives. For instance, even LDPE films (without additives) will have different molecular structures adjusted to give the required thickness, strength and processability. Recycling even such simplified materials to make a material capable of being reused as feedstock for the same plastic film (closed loop) is thus only achievable with waste plastics with a similar composition: in other words, by separating according to each producer's specific product. With general mixed plastics containing different resins, colours and a wide range of additives which are unknown and inseparable, it may become technically impossible to produce a recyclate of any value. This is why downcycling is the norm for any plastics other than PET and HDPE containers, and why waste handlers have depended on low-cost disposal routes through exports. The ideal circular model, in which most plastics can be recycled in a closed loop to new plastic products, can only work so far owing to the inherent technical shortcomings and limitations of the recycling process.

Recycling would be simplified if problematic materials were phased out, which is one expected benefit from properly constructed EPR schemes. In Chapter 4, we pointed to simple guidelines (most of which already exist) that should be factored into EPR schemes with the aim of limiting multi-material packaging based on different and immiscible polymers, and those based on other materials (mainly aluminium and paper), avoiding dark colours, ensuring labels do not obscure the polymer, and incorporating surfaces that facilitate polymer recognition and sorting by NIR.

Additional measures could be considered to incentivise the industry to limit the number of polymers that can be used for specific applications (e.g. for rigid packaging: PET, HDPE, PP and possibly PS; for flexible packaging: LDPE and PP) while restricting small items (which cannot be separated) to just one polymer (e.g. LDPE). Specific roadmaps are now emerging which are industry-led under the plastics pacts (Box 5). There is considerable scope for simplification (for example, the current PET bottle may have a PP cap and a LDPE label, but there is no technical barrier to making all

[31] Plastic Recyclers Europe Press Release, 3 July 2018: 'PET Recycling industry installed capacity reviewed'; see https://plastics-recyclers-europe.prezly.com/pet-recycling-industry-installed-capacity-reviewed#.

components PET). Multilayer films comprising different materials glued together are difficult to recycle, but can be replaced by multilayers based on the same basic resin type (e.g. PE (Butler and Morris, 2013); see examples in Box 9). Moreover, where additives are used, it should be possible, in consultation with the industry, to limit them to those that are compatible with several repeated recycling stages. Improving recyclability is one of the core objectives of the Global and National Plastic Pacts, but these still only attract a minority of the companies involved in plastic packaging (20% in the case of the Global Plastics Pact (EMF, 2019)). Recent studies (Verrips *et al*., 2019a) suggest that regulation to exclude additives and product designs that disrupt the recycling processes can improve recyclability and reduce environmental damage. While it is hoped that a robust EPR system will reinforce trends towards uniform recyclability, the European Commission should monitor progress and consider regulations if the leading companies' examples are not followed by most plastics packaging users.

Despite the potential to strengthen and expand recycling capabilities for those resins in which it is potentially efficient across the whole life cycle, it is important to recognise that there is a balance to be struck between the energy costs of some separation and cleaning processes and the benefits of increased recycling. The value of mixed packaging plastics is so low that intensifying the separation of plastic household waste for recycling under currently available technologies may not be justified from a welfare perspective (Verrips *et al.*, 2019b). For example, Gradus *et al.* (2017) found that the costs of avoided carbon dioxide from improved collection, sorting and recycling were high (€178 per tonne of carbon dioxide in the Netherlands). There will inevitably remain a substantial fraction of mixed plastics where the best (or least bad) solution will be to recover simpler chemical products or energy through chemical treatment, pyrolysis or ultimately incineration with energy recovery (the advanced plastics recovery concept shown in Figure 4). Recycling can thus be subdivided into its own hierarchy as follows (see also Hopewell *et al.*, 2009):

1. The first priority is to recycle to use in the same product as the waste plastic – closed-loop recycling typified by recycling PET bottles to PET bottles. Here, although most PET recyclate is currently downgraded to textiles, bottle-to-bottle recycling has a long history through super-clean technologies (Welle, 2011) and there are market demands to increase recycled PET in bottles (some companies such as Ferrarelle in Italy already use 50% recycled content and Coca-Cola has a target of 50% recycled content by 2023 in Europe). Other, more recent technologies break down PET to its constituent monomers (terephthalic acid and ethylene glycol) before re-polymerising[32].

2. The second is to recycle for use in another plastic product (especially where quality cannot be maintained, this will be for lower-quality uses: downcycling). HDPE is commonly recycled into plastic bins or lumber; PET into textile fibre.

3. Third would be extracting valuable chemicals or fuels through chemical treatment or pyrolysis: molecule recycling. As described in section 4.1, there are several potential processes currently under development.

4. Finally, where the above are not feasible, to extract energy from the remaining plastic waste: energy recovery.

Technological development should continue to improve the net energy and resource savings offered by technologies in stages 1–3 and to reduce costs, while regulations should encourage the contributions of available technologies within this hierarchy.

A fundamental barrier to a more circular model is the competition between virgin raw materials and recycled materials. Virgin prices continue to be low because of low oil and gas prices which are in turn influenced by megatrends such as the American shale gas revolution. This has delivered low prices from natural gas primarily because social and environmental costs are externalised; operators do not pay for the externalities of methane leakage and its substantial contribution to global warming, or to water pollution (Hausman and Kellogg, 2015; Mason *et al.*, 2015), and some operators abandon wells and thus avoid post-closure costs. Moreover, gas (along with oil and coal) pays no carbon price in the USA or other primary producing countries. The net result is that the price of primary fossil fuels is much lower than the social optimum and this in turn leads to low virgin prices for plastics which leads to higher rates of consumption and cost barriers to replacing virgin with recycled plastics[33]. This has been cited to support the idea of a tax to reflect the negative externalities of virgin plastics (Box 13).

The European Commission has proposed a contribution based on amounts of plastic packaging waste that is not recycled as an additional source of revenue for the EU budget. This Own Resource to be provided

[32] For example, CARBIOS (https://carbios.fr) and Ioniqa (https://ioniqa.com).
[33] See also the problem tree analysis to identify the main drivers of plastic pollution problems in section 4.4 of Eunomia/ICF (2018).

Box 13 A plastics tax?

The leakage of plastic packaging into the environment causes damage the costs of which are not borne by the manufacturers or consumers, and thus there is a lack of direct market incentives for consumers to restrict their use or dispose responsibly, or for retail outlets to provide or encourage return and recycling. A simple market-based policy response would be to internalise these costs, but this is far from straightforward. While some negative impacts can be monetarised (e.g. clean-up costs, physical damage to fishing or tourism) and have been estimated at around $13 billion by UNEP (2014), others cannot (Newman *et al.*, 2015). The latter impacts involve ethical questions about humankind's respect to the existence of other species (in the case of turtles, whales or birds killed by entanglement or ingestion) or economic impacts which cannot be quantified owing to lack of data (e.g. loss of a fisheries' productivity through plastic affecting primary productivity or weakening individuals through ingestion). Moreover, substantial environmental externalities (including the major contributions of fossil fuels to global warming) also apply in the extraction of fossil fuels, and refining to produce monomer and polymerisation to produce the plastics.

One policy option to address this market failure is to apply a tax to plastics to reflect the negative externalities of their production, use and leakage to the environment (a 'Pigovian' tax). A review by the New Economics Foundation (2018) presented an analysis of the role of such a tax in influencing consumer behaviour, internalising the costs of environmental damage caused by the sources of the pollution and raising revenue for pro-environmental expenditure (such as strengthening recycling infrastructure). It examined options for application at the various points along the value chain in Figure 2 and concluded that taxes could play a strong and central role in stimulating a more circular use pattern for plastics. Further research was called for to clarify the response of producers and consumers, the costs of monitoring and enforcement, and to avoid perverse incentives to switch from plastics to materials with a greater environmental impact. OECD (2018b) also notes that governments could level the playing field between virgin and recycled plastics by *inter alia* applying taxes on the use of virgin plastics, setting recycled content standards, targeted public procurement requirements or recycled content labelling; as well as addressing the low fossil fuels prices by reforming current support for fossil fuel production and consumption.

Some EU countries are considering a tax to be applied to virgin plastics as a means of incentivising the use of recycled plastics and helping meet the targets of the SUP Directive which aims for 25% of recycled plastic in PET bottles from 2025, and 30% recycled content in all plastic bottles from 2030. Applying such a tax involves issues of transparency, implementation and applicability over national boundaries. Moreover, a contribution related to the non-recycled plastics in Member States is under consideration as a means of additional own sources of revenue to the EU budget. Initial figures in discussion with Member States would comprise a charge of €0.8 per kilogram of plastic packaging waste that is not recycled (https://www.consilium.europa.eu/en/policies/eu-budgetary-system/eu-revenue-own-resources/2021-2027/).

by Member States could be justified by the negative externalities associated with plastics production, use and leakage into the environment as well as contributing to a reduction in material flows. It would be for Member States to consider whether and how to reduce their own country's use of plastics to limit their contribution. They would, of course, have the possibility of recouping their contribution by imposing a plastics tax, although at present this appears not to be the preferred option for most Member States. Further examination is warranted on whether this option can reinforce the effects from the enhanced EPR system described above, or lead to perverse incentives to switch from plastic packaging to materials with more adverse environmental impacts. One consideration is that the current low-cost waste recycling industry appears unlikely to be able to support the capital investment challenges of increasing recycling capacity and developing and applying emerging technologies. Increased income from such taxes could be one option for providing loans or other support measures for the necessary capital investment.

8.7 Labelling of recyclable materials

A related but separate issue is that of labelling. Although evidence is that consumer labelling may only be read by a fraction of consumers, its presence on packaging conveys the message that manufacturers have considered recyclability in their choice of packaging. The situation in the EU is that there are different systems in different countries and that it is voluntary (Figure 10 shows symbols for UK[34], France and Germany/Sweden and other countries). Consumers are thus faced with varying symbols and, in many cases, no symbols at all. In contrast, Japan has a consistent set of symbols (Figure 11) that are applied to all packaging, however small, allowing local areas to require more precise separate collection systems that deliver higher-quality feedstock to recycling plants.

Internationally, there are resin identification codes used in some products which merely identify the plastic resin irrespective of whether it is recyclable. Consumers are thus faced with potentially multiple symbols which may not relate to local recyclability at all. This may reduce their value as a means of improving recycle rates and run counter to the findings of behavioural research (Chapter 5) that consumers require information that is simple, reliable and trustworthy. The spread of automated separation systems that allow collection of mixed plastics of different resin types may reduce the need for consumers to rely on labels; even so, a more uniform and simple coding related to actual (rather than theoretical) recyclability could be beneficial. The

[34] The UK On-Pack Recycling Label scheme (OPRL) designed to support the UK Plastics Pact to ensure that design aids easy separation and high value recycling of components.

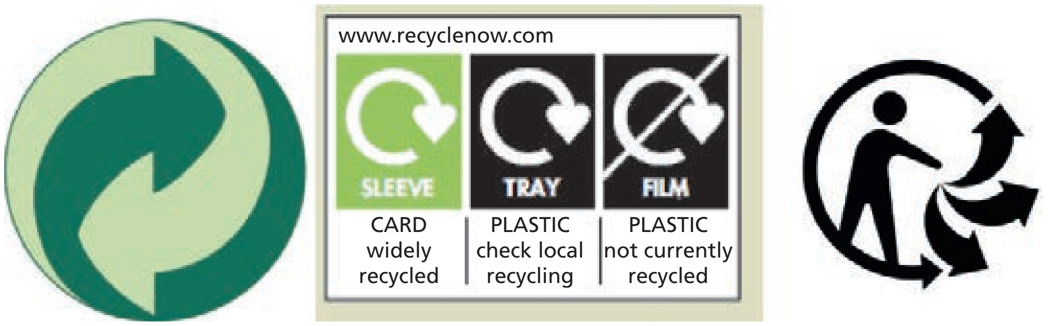


Figure 10 Recycle labels in use in various EU countries (from left: a widely used symbol in Germany, Sweden and elsewhere; the UK; France).

Figure 11 Japan's recycle symbols.

adoption of such a unified system, however, does require that the opportunities for recycling are uniform across the EU, which the Expert Group considers should be one of the longer-term objectives of EU policy.

8.8 Single-use plastics

The European Commission's strategy to substantially reduce leakage of SUPs was described in section 2.3. Some SUPs are targeted for bans, with items such as plastic straws, plates and cutlery banned by 2021. Others will be subject to EPR. While some of these needs can be met by substitution (paper straws, wood stirrers, etc.), others require a change in convenience-focused behaviours made possible by the availability of plastic goods. The growth in 'on the go' consumption of food and beverages has taken place with outlets relying on basic refuse collection services to avoid littering. Integrating recycle loops into the many dispersed outlets (e.g. for coffee cups, or fast-food trays and wrappers) requires a substantial change in both retail and consumer behaviour with reverse logistics and significant staff time and resources. Some leading chains[35] have started to experiment with their own collection and recycling systems, but the Expert Group considers that these initiatives should be supported by regulations assigning a duty on retailers to provide on-site collection for the packaging they sell.

The social science evidence relevant to consumer behaviour shows that consumers are influenced by prices: not only because of the financial incentives associated with them, but also because they help signify a new social norm. The experience of charges for plastic bags shows that even small charges can be extremely effective, especially when the reasons for the charges are effectively communicated and attract majority public support. The Expert Group notes that the plastic bag charge has become a model of how to change consumer behaviour and recommends that deposit systems be extended to a broader group of containers, or systems offering discounts for customers who use

[35] For example, the UK's biggest coffee chain, Costa Coffee, has said it will recycle as many disposable cups as it sells by 2020 — some 500 million coffee cups a year. Starbucks is trialling cup recycling or use of compostable cups, while other retailers are switching to reusable cups.

their own containers. Such measures can encourage consumers to see packaging as being 'on loan' and therefore returnable to be efficiently reprocessed (preferable via closed-loop recycling). In this context, it was noted earlier that separate charges for containers such as coffee cups are more effective in reducing demand than offering discounts on own containers.

Some types of PHA plastic show a degree of biodegradability in marine and other environments (Deroine *et al.*, 2015; Jacquin *et al.*, 2019), suggesting that one means of reducing environmental impact of such extensively littered products would be to require some of the SUP materials to use PHA. However, rates of degradation are still slow and further development and validation of any claims for biodegradability are necessary before this could be supported as a means of reducing the environmental impact of SUPs.

8.9 Protecting the environment

Annex 2 summarises evidence on the impacts of **macroplastics and microplastics**. The visible images of marine life being entangled or killed by macroplastics has been supplemented by more general concerns over the extensive contamination by microplastics, whose emissions into the environments are estimated at approximately 11.7 million tonnes per year (Boucher *et al.*, 2017). 'Primary' microplastics arise from road markings, tyre wear, textile washing and other terrestrial sources (including 'microbeads' used in cosmetic and other products and abrasives used in ship blasting) and amount to 3.2 million tonnes per year (Hann *et al.*, 2018). The remainder of marine microplastic inputs comes from 'secondary' microplastics which arise from weathering and fragmentation of larger plastic items in the environment.

As noted in Annex 2, laboratory experiments have demonstrated possible adverse effects of microplastics through both physical and chemical toxicity. Physical effects include inflammation and stress, blocking the gastrointestinal tract and interfering with respiration. Exposure to microplastics can thus reduce food consumption, growth, reproduction and survival. Toxic exposure thresholds clearly vary with the species affected, the amounts of microplastic, their shape and size, and whether toxic chemicals or additives are absorbed. Many scenarios exist and dose–response relationships are not generally available. The Expert Group also notes that a lack of data on actual environmental levels makes it difficult to assess the degree of risk in the environment and whether there are likely to be any significant effects in the field at organism or ecosystem levels. Further work is thus required to better assess risks in marine, freshwater and terrestrial environments.

As pointed out in Annex 2, it is still unclear how far small plastic particles have different effects than naturally occurring sediments or organic particles of similar size in the seas, or in soils. This is in contrast to the many studies that have demonstrated the adverse effects of macroplastics especially on marine life. Consequently, the established adverse effects of macroplastics and their importance as a source of microplastics would support regulatory action continuing to focus on macroplastics. Deliberate addition of microplastics by companies to products that will enter the environment should be avoided. Such actions without adequate evaluation and prevention measures to their potential environmental effects are classic examples of the polluter pays principle and precautionary principles being ignored. The Expert Group thus supports the European Commission's approach to assess costs and benefits through the Registration, Evaluation, Authorisation, Restriction of Chemicals (REACH) Directive.

Nevertheless, the extent to which microplastics are contaminating the environment from the deep ocean to the Polar seas, from drinking water to seafood, raises issues that are not readily addressed by standard evidence-based risk analysis. Assessments of human health impacts of plastics contamination are generally associated with a call for more research to supplement the limited knowledge available[36]. However, concerns have been expressed at the possible presence of toxic chemical additives in plastic particles which can leach out if ingested and form an exposure pathway to humans (see, for example, Vethaak and Leslie, 2016), while plastic debris can also act as a surface for pathogenic microorganisms and parasites (see Kirstein *et al.*, 2016). A critical policy issue is thus the extent to which the precautionary principle should be applied to consider not just the effects on the marine, freshwater and terrestrial environments but also potential impacts on human health. Here Backhaus and Wagner (2018) have summarised the implications for actions that might follow adopting the precautionary principle (Table 6), and a debate within society is required to determine the degree to which this is applied.

8.10 International aspects

The extent to which the major sources of leakage into the marine environment lie outside the EU has already

[36] For example, the WHO (2019) recent statement on human health risks from microplastics in drinking water concludes, '*Based on this limited body of evidence, firm conclusions on the risk associated with ingestion of microplastic particles through drinking-water cannot yet be determined; however at this point, no data suggests overt health concerns associated with exposure to microplastic particles through drinking-water.*'.

Table 6 Comparing an evidence-based and precautionary principle approach to microplastics (Backhaus and Wagner, 2018)

	Strictly evidence-based approach	Precautionary approach
Arguments in favour	Insufficient knowledge • Low exposure (on current estimates) • Low toxicity (on current knowledge) • Presence of natural particles at higher levels • Likelihood of negative impacts low	Sufficient knowledge • Ubiquity • Persistence • Mobility in food web • Increasing emissions • Part of macroplastics problem where sufficient knowledge on impacts exists • Existence of unknown, negative impacts
Actions needed	• Identify knowledge gaps • Perform more research filling these gaps • Conduct risk assessment • Take risk decision • Depending on outcome: develop and implement risk management measures	• Take risk decision • Develop and implement risk management measures based on fragmentary knowledge • Perform research into the effectiveness and efficiency of these measures • Refine measures
Advantages	• Avoids inefficient risk management measures • Avoids unnecessary opportunity and unintended externality costs • Avoids regrettable substitutions **Reduces cost of action**	• Early action avoids negative impacts later • Motivates positive societal and economic change (vision of a better society) • Fosters technological and societal innovation **Reduces cost of inaction, induces change**

been emphasised. As noted by Dauvergne (2018), the difficulty of governing global use of plastic has been exacerbated by the rise in production, consumption and international trade so that sources of pollution and responsibility for them are highly diverse; at the same time, regulations are fragmented across nations and localities. Despite the stated aims to reduce plastic pollution by leading international brands in the Global Plastics Pact, industry efforts to resist local regulation (e.g. of microbeads or plastic bags) remain strong[37]. The EU should thus support UNEP and other initiatives to reduce leakage globally. There are a variety of EU support and development policies, grants and programmes aimed at developing regions[38]. It is recommended that the EU make use of these resources to help the regions develop waste management systems where much of the plastic waste leaks into the environment, with the aim of terminating plastic waste leakage globally (see OECD, 2018b). The EU should also encourage the World Bank and other international aid agencies to support effective and environmentally sound waste collection, sorting and recycling infrastructure, as they move away from supporting fossil-fuel development.

The EU should also ensure that Member States cease to contribute to further leakage through mismanagement of their own exports. The EU should lead in rejecting the export of its problematic waste to countries less able to cope with it, and seek to embed this principle further internationally by playing an active role in the Stockholm[39], Basel and Regional Seas Conventions and other efforts (such as the 2020 UN Oceans Conference) to strengthen global governance related to plastic waste in the oceans (Raubenheimer and McIlgorm, 2018; UNEP, 2018b). With the reluctance of some countries (e.g. Japan and the USA abstaining from the ocean's plastic charter within the Group of Seven (G7); the US opposition to amending the Basel Convention), there is also a role for environment and science diplomacy.

8.11 Bio-based plastics

Applying the label of 'bio' offers a marketing option which has been taken up by some companies in labelling their PET bottles. However, alternative feedstocks can have major sustainability impacts (on land and water use, biodiversity, indirect GHG emissions and creating competition with food production) as is

[37] In the USA, pre-emption laws prohibit municipalities from adopting local ordinances that further regulate a particular product such as bans or fees on plastic bags or other containers. Such laws have already been passed, or are being proposed in more than 20 US states. (https://www.plasticbaglaws.org/preemption).
[38] See https://ec.europa.eu/europeaid/general_en
[39] An evaluation for the regional centres of the Stockholm and Basel Conventions concluded (Gallo *et al.*, 2018) that chemical additives and contaminants in plastics packaging included some known endocrine-disrupting chemicals and posed potential risks to marine ecosystems, biodiversity and food availability. Subsequently, it was agreed that preventative measures for plastic waste and a fundamental rethink of the ways in which we consume plastics would be further examined.

already a concern over current demand for crops for biofuels and bioenergy (e.g. Searchinger, 2009; PBL, 2012; EASAC, 2013; 2017c; IPBES, 2019). Moreover, with current technologies, bio-based plastics cannot be scaled up to meet more than a fraction of potential demand. Thus, even though there are applications where biopolymers are excellent, their overall merits should be evaluated on the basis of full LCAs, rather than on simplistic assumptions or claims that 'bio' signifies a lower environmental impact. The Expert Group considers that, to avoid misleading consumers, companies should have quantified any environmental benefits to support any such claims and that further improvement in the LCA methodology should be researched further.

8.12 Biodegradability and compostability

As discussed in Chapter 6, the ideal target of a plastic that breaks down naturally in the environment remains elusive. Natural environments vary in temperature, humidity, degrading microorganisms and many other factors, so that degradation is difficult to engineer into the plastic molecule. Only a limited number of products show a degree of biodegradability in the marine environment and even those still maintain their integrity for months during which time the negative effects of entanglement, ingestion and other issues will remain. Rapid biodegradability remains in conflict with primary requirements for plastic packaging (stability, durability, etc.) and thus cannot at present offer an alternative to measures to reduce littering and release of plastics into the environment.

Compostability in an industrial composter is achievable with several resins, but extension to wider consumer use is problematic owing to the limits of home composting and the adverse effects on recyclate quality when compostable blends end up mixed with other plastics. At the present state of technology, composting makes sense only when the plastic is contaminated by a substance that is also disposed of by composting: for example, compostable bags used in the closed loops of food waste recycle.

Overall these limited applications are no panacea for the main problem of mass production and use of plastics and the associated leakage into the environment. Furthermore, research has not yet developed an environmentally benign plastic packaging which combines rapid degradation into naturally recyclable components with the necessary functionality and cost-effectiveness.

8.13 Research and innovation

As briefly described in Chapter 7, research and innovation offer many possibilities; regulations thus need to ensure that they are flexible and incentivise those innovations that meet the key objectives of reducing overall material usage and eliminating leakage.

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Annex 2 Plastics and the environment

As reviewed by Horton and Dixon (2018), plastics entering the environment as packaging items can break down by physical (e.g. mechanical abrasion), chemical (e.g. loss of plasticisers leading to embrittlement), photo-oxidative or (to a limited degree) biological processes to secondary microplastics. As packaging use in consumer products is mostly on land, together with industrial spillage and use in agriculture, initial leakage through littering or inadequate waste management is mostly to the land and adjoining freshwater environments. From there, plastic materials ranging from the original product to microplastics and nanoplastics may remain within the terrestrial environment (e.g. in soils), in freshwater bodies such as lakes or be transported via rivers to the sea, where they join plastics added directly to the marine environment from coastal leakage or direct leakage from marine sources (ships, fishing, aquaculture, etc.). Reverse transport processes may also exist: for instance, collection of microplastics from sewage may return to agricultural land through sewage sludge used as a fertiliser.

Substantial research has been done on the impacts of plastics in the marine environment, which are summarised in the next section (Annex A2.1). However, studies of the fate and effects of plastics in terrestrial and freshwater environments have been much more limited – especially the latter which includes rivers, lakes and small streams or even groundwater (Panno *et al*. 2019) – all with very different characteristics. Thus, major uncertainties remain in the summary of our knowledge given in Annex A2.2.

Whichever compartment of the environment may be involved, harm from plastic pollution may occur from its physical effects: ingestion may block, or lacerate the stomach and digestive systems. Chemical additives in the plastic (or absorbed and accumulated from low levels of environmental contaminants such as PCBs) may also may be taken up by organisms following ingestion.

A2.1 Plastics and the marine environment

A2.1.1 Sources and distribution

Plastics enter the marine environment as follows.

Directly from

- fishing-related debris (fish/lobster traps, crab pots, fishing lines, floats, and nets);
- food- and beverage-related litter along the shoreline (e.g. bottles, cans, lids, food wrappers, bags and disposable cups, plates, straws, plastic cutlery);
- smoking-related litter (cigarette filters, cigar tips, disposable lighters);
- manufacturing and transportation-related waste (e.g. resin pellets losses, pallets, plastic sheeting and straps, waste dumped from vessels).

Indirectly from

- land — plastics (e.g. bags or sheeting) blown out to sea;
- rivers carrying plastic waste dumped directly or washed off from land;
- sewage treatment discharges direct to the sea or via rivers where even secondary treatment will allow smaller particles to pass.

The nature of the plastics discharged covers the full range of resins combined with additives of varying levels of toxicity (Hahladakis *et al.*, 2018), potential pollutants absorbed by plastic particles, and a range of sizes from large (ropes, bags, etc.) to fragments down to the nanometre scale. Regarding quantities, Jambeck *et al.* (2015) calculated that 4.8–12.7 of the 275 million tonnes of land-based plastic waste generated in coastal countries in 2010 had entered the ocean. Other studies (e.g. Eriksen *et al.*, 2014) calculated (on the basis of data from trawls) that from 5 trillion to 50 trillion particles with a cumulative mass of 32,000 to 236,000 tonnes were in the world's seas. Microplastics (generally defined as less than 5 mm in diameter) have been found in the remotest areas including the Arctic Ocean (Lusher *et al.*, 2015) and in the Southern Ocean (Barnes *et al.*, 2009). They have also been found in the deepest parts of the ocean trenches (Peng *et al.*, 2018). High concentrations are found in the subtropical gyres of the North and South Atlantic, North and South Pacific, and the Indian Ocean, where concentrations of plastic can be a million times higher than in other regions such as the tropical Pacific and Southern Oceans. High concentrations are also found in seas adjoining highly populated areas such as the Mediterranean Sea (GESAMP, 2015). Other studies showed that the dominant resin types (in excess of 90%) found in plastic litter in freshwater and marine environments were the polyolefins and polystyrene (Schwarz *et al.*, 2019).

A major source is from river discharges; Schmidt *et al.* (2017) and Lebreton *et al.* (2017) calculate that rivers carry 0.47 million to 2.75 million tonnes of plastic into the seas every year. Ten rivers (Yangtze, Yellow, Hai he, Pearl, Amur, Mekong, Indus and Ganges Delta in Asia, and the Niger and Nile in Africa) account for 93% of the total discharged by rivers. Figure A2.1 shows the areas where plastic waste is produced and the fraction of the waste which is mismanaged and liable to leak into the environment (Jambeck *et al.*, 2015).

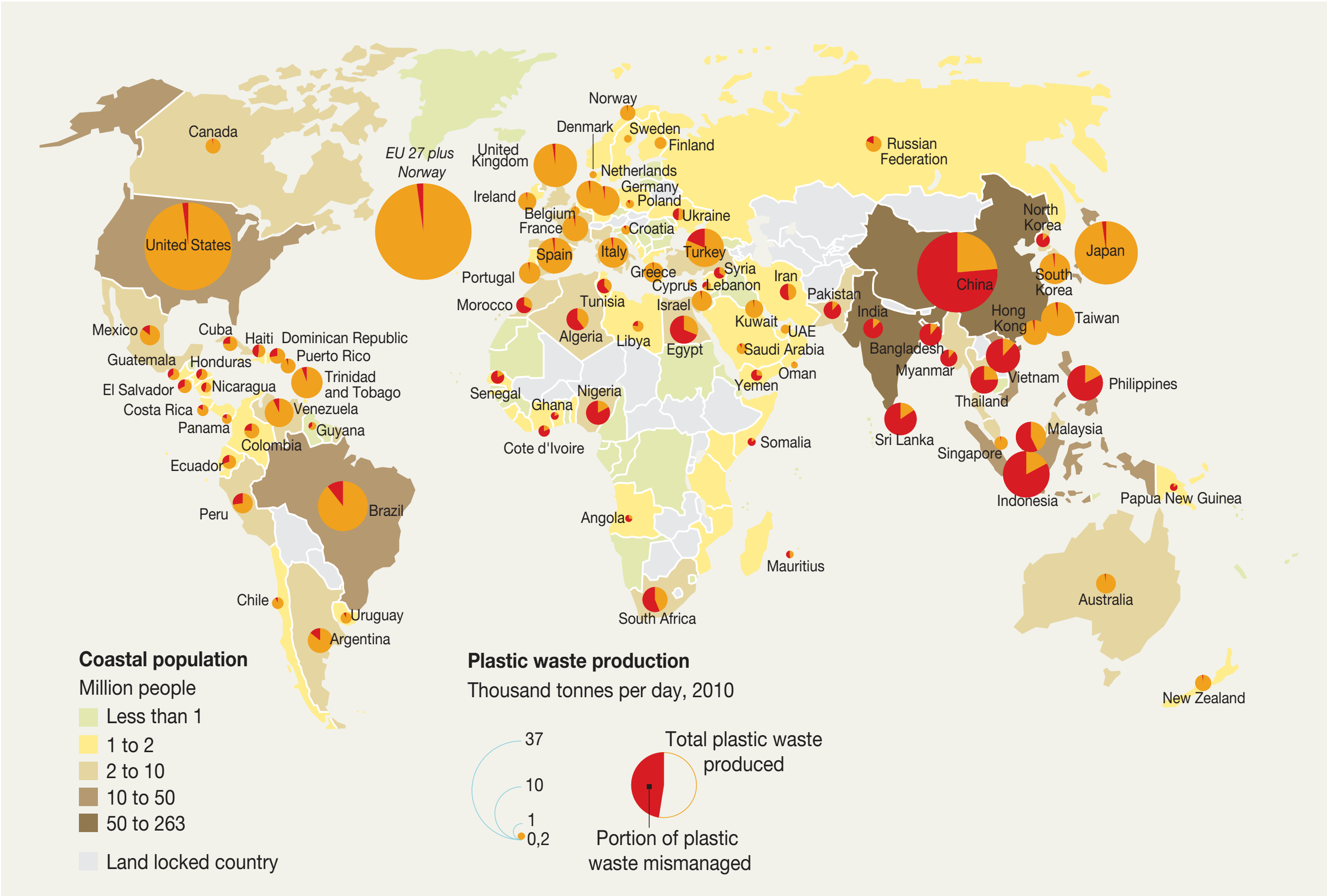

Figure A2.1 Estimated quantities of plastic waste produced and proportion recycled (based on Jambeck et al. (2015) as shown in GESAMP (2016)). Reproduced from GRID-Arandal (https://www.grida.no/resources/6931; created by Maphoto/Riccardo Pravettoni).

A2.1.2 Environmental and human health impacts

JRC (2016) summarises the impacts of plastic litter in the marine environment as '... through *entanglement in, or ingestion of, litter items by individuals, resulting in death and/or severe suffering; through chemical and microbial transfer; as a vector for transport of biota and by altering or modifying assemblages of species. Marine litter is a threat not only to marine species and ecosystems but also carries a risk to human health and has significant implications to human welfare, impacting negatively vital economic sectors such as tourism, fisheries, aquaculture or energy supply and bringing economic losses to individuals, enterprises and communities.*'

Chemical additives also enter the global oceans in common plastic debris items, while plastics can also act as a means of absorbing trace contaminants already present in the marine environment and concentrating them up to levels that may have toxicological impacts if ingested. As already noted in Chapter 3, Zimmermann *et al.* (2019) found that unidentified components in consumer plastics (PP, LDPE, PS and PLA) exhibited a range of toxicological effects in *in vitro* studies, while Groh *et al.* (2019) found that among the chemicals commonly associated with packaging plastics were 63 associated with human health hazards and 68 with environmental hazards, with 7 classified in the EU as persistent, bio-accumulative and toxic. Frond *et al.* (2018) estimated that the quantities of 20 of such chemicals could amount to 190 tonnes, while microplastics in coastal areas were associated with high levels of PCBs, suggesting that plastics are a path for potentially toxic chemicals both to enter and to be redistributed in the marine environment.

Discussing the effects of plastics in the marine environment often differentiates between macroplastics and microplastics, with a boundary of 5 mm between the two.

A2.1.3 Macroplastics

Entanglement and ingestion of macroplastics debilitate, mutilate or kill millions of marine animals each year (Butterworth *et al.*, 2012), with over 500 marine species shown to be affected by marine litter (SCBD, 2012), of which the most visible are birds, turtles and mammals. Entanglement has been found in *all* species of marine turtles, 22 species of seals, 25 species of whales, 103 species of seabirds, 89 species of fish as well as 92 species of invertebrates. Observations suggest that globally from 57,000 to 135,000 pinnipeds

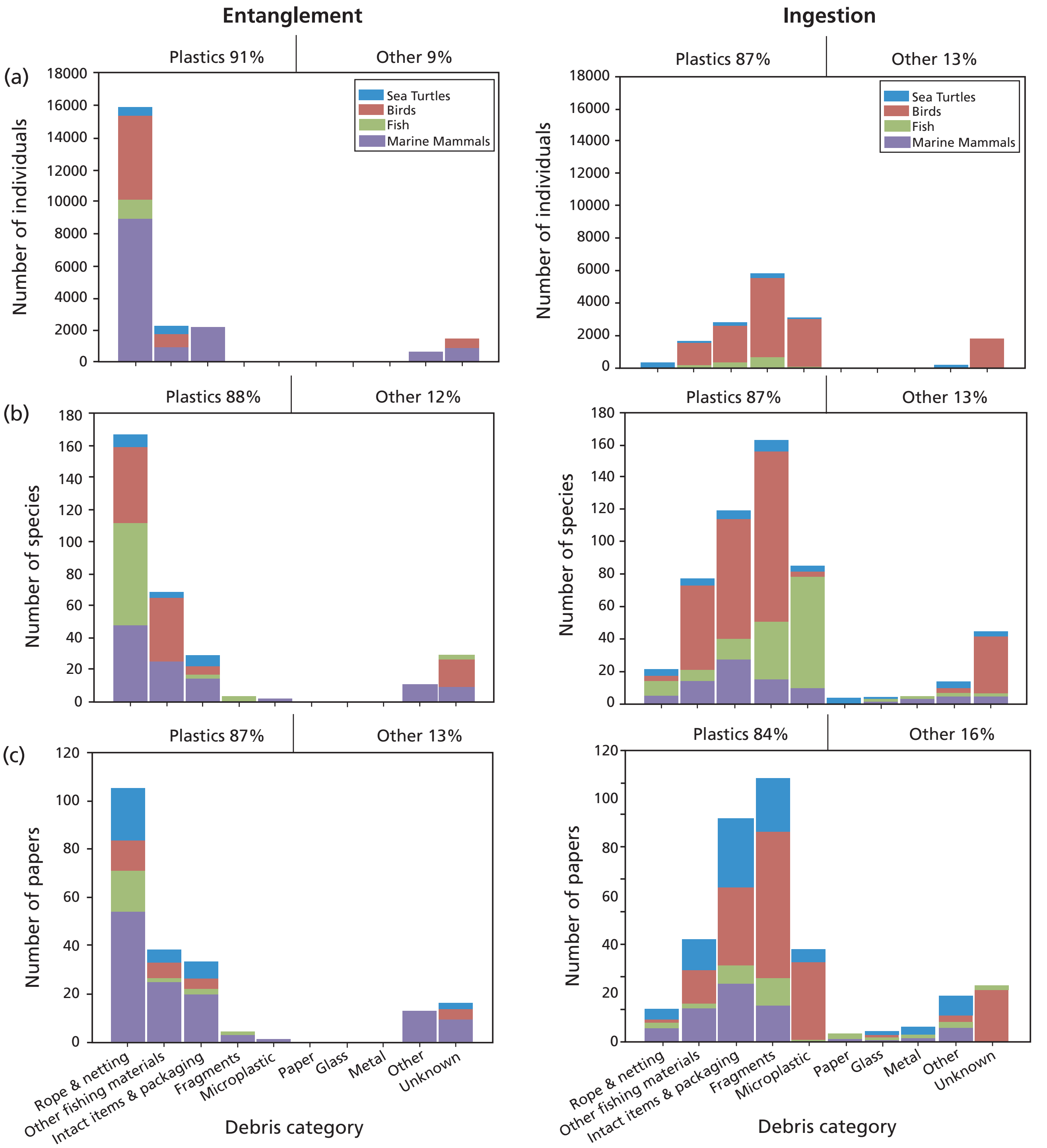

Figure A2.2 Impacts of marine debris marine life (Gall and Thompson, 2015).

(seals and related species) and baleen whales are entangled each year, in addition to probably millions of birds, turtles, fish and other species. Only 3% to 10% of entanglements are likely to be witnessed and reported, and the vast majority thus remains undetected.

The plastics mostly responsible are net fragments, rope and line (e.g. gill and trawl nets, lost or discarded line for pots and traps), monofilament line, packaging bands, plastic circular rings and multipack can rings (Butterworth *et. al.*, 2012) as well as balloons and plastic bags. Such effects are widespread; for instance, in the North Sea, 93% of the fulmars analysed had ingested plastics (van Franeker *et al.*, 2011), while in a survey of turtles in the Mediterranean and Northeast Atlantic, 85% of the 120 individuals analysed contained ingested litter (Matiddi *et al.*, 2017). A review by Gall and Thompson (2015) provides a breakdown of reported effects for different species groups (Figure A2.2).

Entanglement can be immediately fatal such as when a marine mammal cannot resurface and drowns; or it reduces mobility and agility which makes the animal more vulnerable to predators or boat strikes or (together with ingestion) interferes with feeding, leading to starvation. Growth while entangled leads to tissue damage including laceration of large blood vessels (also fatal). While effects are seen at an individual level, the rate of increased mortality is sufficiently high to affect populations through loss of adults and offspring. For instance, the mortality rate of adult gannets has increased some 10-fold owing to entanglement.

Ingestion can cause direct physical damage to the intestine through perforations, inflammations and ulcerations, and plastic that accumulates in stomachs may slow down digestion or give signals of satiation which reduce appetite, leading to starvation. Autopsies on stranded whales and other marine life show a propensity to eat large items such as plastic bags either eaten as mistaken prey or accidentally ingested while feeding.

The adverse impacts from macroplastics are thus dominated by the obvious effects on individuals and likely effects at the population level — primarily biodiversity and animal welfare concerns. These have been sufficient to justify policies aimed at eliminating plastic waste, as recognised in the EU and G7 in 2018 (Box A2.1). Also, the UN General Assembly adopted a resolution on similar lines[40].

A2.1.4 Microplastics

Macroplastics break down (primarily through exposure to ultraviolet light and physical abrasion) into fragments of various shapes and sizes, which are regarded as **microplastics** when they are smaller than 5 mm. In addition, small particles arise from breakdown during the use of several major products (e.g. from tyre abrasions, from textiles during washing, from marine paints). Furthermore, microplastics are used as an industrial abrasive (e.g. in ship cleaning), and are added to some household products from where they may enter the marine environment directly or via sewage treatment discharges (see Figure 1 in Hann *et al.*, 2018). However, as can be seen from Figure A2.3 (Van Franeker *et al.*, 2011), organisms may be affected by plastics of any size and the difference can be somewhat arbitrary.

International reviews have brought together available scientific evidence on sources, types of microplastic and potential risks at individual and ecosystem levels (Cole *et al.*, 2011; GESAMP 2015, 2016; Auta *et al.*, 2017). As noted earlier, microplastics are widespread in the marine environment and are ingested by all marine organisms ranging from marine birds and mammals, through fish, to invertebrates such as crustaceans, mussels and zooplankton. The finer-sized particles can even reduce the efficiency with which primary phytoplankton absorb carbon dioxide (Bhattacharya *et al.*, 2010).

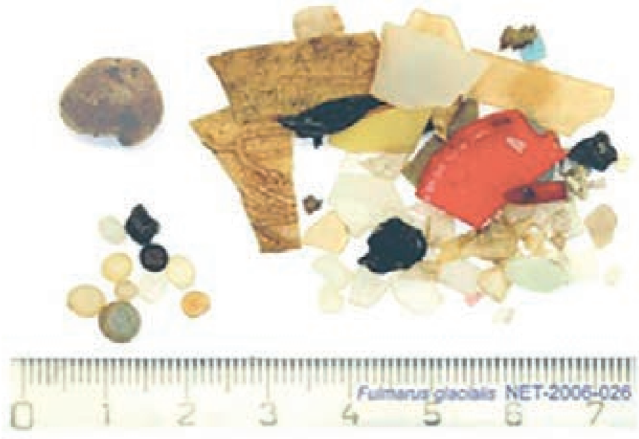

Figure A2.3 Fragments of plastic in the stomach of a northern fulmar in the North Sea (figure 3.6 in GESAMP, 2015).

Given the almost infinite potential combinations of plastics – particle size, particle shape, crystallinity, surface chemistry, and polymer and additive composition (Lambert *et al.*, 2017) and their potential interactions throughout the marine ecosystem (Galloway *et al.*, 2017) – conducting an analysis of the risks to marine organisms is fraught with difficulty. A fundamental question is to what extent ingesting small particles that are plastic differs from the natural particles of sediment or natural organic material of similar size (Backhaus and Wagner, 2018; Ogonowski *et al.*, 2018). Some organisms will excrete indigestible particles, while others may retain particles above a certain size in their stomach, resulting in malnutrition or starvation, and transfer to higher trophic levels. Laboratory tests inevitably have to simplify to a single type of plastic (often a plastic pellet) and single marine organisms. The wide range of tests reviewed by GESAMP (2015, 2016) show the nature of potential adverse effects to include physical effects (physical obstruction or damage of feeding appendages or digestive tract or other physical harm) and the potential for chemical effects resulting from the additives in plastic, or from contaminants

[40] 2018 UNEA Resolution 3/7: Marine litter and microplastics https://papersmart.unon.org/resolution/uploads/k1800210.english.pdf

Box A2.1 G7 Oceans Plastic Charter 2018 (Japan and USA refused to sign)

We commit to take action towards a resource efficient lifecycle management approach to plastics in the economy by:

1. **Sustainable design, production and after-use markets**
    a. Working with industry towards 100% reusable, recyclable, or, where viable alternatives do not exist, recoverable, plastics by 2030.
    b. Taking into account the full environmental impacts of alternatives, significantly reducing the unnecessary use of single-use plastics.
    c. Using green public procurement to reduce waste and support secondary plastics markets and alternatives to plastic.
    d. Working with industry towards increasing recycled content by at least 50% in plastic products where applicable by 2030.
    e. Supporting secondary markets for plastics including using policy measures and developing international incentives, standards or requirements for product stewardship, design and recycled content.
    f. Working with industry towards reducing the use of plastic microbeads in rinse-off cosmetic and personal care consumer products, to the extent possible by 2020, and addressing other sources of microplastics.
2. **Collection, management and other systems and infrastructure**
    a. Working with industry and other levels of government, to recycle and reuse at least 55% of plastic packaging by 2030 and recover 100% of all plastics by 2040.
    b. Increasing domestic capacity to manage plastics as a resource, prevent their leakage into the marine environment from all sources, and enable their collection, reuse, recycling, recovery and/or environmentally-sound disposal.
    c. Encouraging the application of a whole supply chain approach to plastic production towards greater responsibility and prevent unnecessary loss, including in pre-production plastic pellets.
    d. Accelerating international action and catalyzing investments to address marine litter in global hot spots and vulnerable areas through public-private funding and capacity development for waste and wastewater management infrastructure, innovative solutions and coastal clean-up.
    e. Working with relevant partners, in particular local governments, to advance efforts to reduce marine litter and plastics waste, notably but not exclusively in small island and remote communities, including through raising awareness.
3. **Sustainable lifestyles and education**
    a. Strengthening measures, such as MBIs, to prevent plastics from entering the oceans, and strengthening standards for labelling to enable consumers to make sustainable decisions on plastics, including packaging.
    b. Supporting industry leadership initiatives and fostering knowledge exchange through existing alliances and other mechanisms.
    c. Promoting the leadership role of women and youth as promoters of sustainable consumption and production practices.
    d. Support platforms for information sharing to foster awareness and education efforts on preventing and reducing plastic waste generation, plastics pollution and eliminating marine litter.
4. **Research, innovation and new technologies**
    a. Assessing current plastics consumption and undertaking prospective analysis on the level of plastic consumption by major sector use, while identifying and encouraging the elimination of unnecessary uses.
    b. Calling on G7 Ministers of Environment at their forthcoming meeting to advance new initiatives, such as a G7 Plastics Innovation Challenge, to promote research and development of new and more sustainable technologies, design or production methods by the private sector and innovators to address plastics waste in the oceans with a focus on all stages of the production and supply chain.
    c. Promoting the research, development and use of technologies to remove plastics and microplastics from waste water and sewage sludge.
    d. Guiding the development and appropriate use of new innovative plastic materials and alternatives to ensure they are not harmful to the environment.
    e. Harmonizing G7 science-based monitoring methodologies.
    f. Collaborating on research on the sources and fate of plastics and their impact on human and marine health.
5. **Coastal and shoreline action**
    a. Encouraging campaigns on marine litter in G7 countries with youth and relevant partners to raise public awareness, collect data and remove debris from coasts and shorelines globally.
    b. Accelerating implementation of the 2015 G7 Leaders' Action Plan to Combat Marine Litter through the Regional Seas Programs, initiatives led by RFMOs, where appropriate, and targeted investments for clean-up activities that prove to be environmentally sound in global hotspots and priority areas, in particular on Abandoned, Lost or Otherwise Discarded Fishing Gears (ALDFG) and wastes generated and collected by fishery activities.

selectively absorbed from the environment[41]. Experiments have also shown that the smallest particles can cross from the gut to other tissues and are capable of crossing cell membranes and causing inflammation and cell damage. Microplastics in prey may be taken up by predators, and by filter-feeding invertebrates, such as mussels or oysters and thus provide a route of human exposure[42].

A recent meta-analysis of published literature (Foley *et al.*, 2018) found that the effects of exposure to microplastics are highly variable across taxa, with many

[41] Laboratory study showed that common additives such as phthalates affect reproduction in all marine species studied and impair development in crustaceans, as well as inducing genetic aberrations (Oehlmann *et al.*, 2009). Tanaka *et al.* (2013) showed polybrominated compounds transferred from plastics to birds.
[42] Van Cauwenberghe and Janssen (2014), on the basis of amounts found in European shellfish, calculated that the average shellfish consumer eats 6400 microplastics per year. For fish, Lusher *et al.* (2013) found that one-third of fish caught off the southwest coast of England were contaminated with plastic fragments.

studies showing little effect. The most consistent effect was a reduction in consumption of natural prey when microplastics were present. For some taxa, negative effects on growth, reproduction and even survival were also evident. The key factor in assessing the scale of risks in the environment is the extent to which environment concentrations approach those using laboratory testing; here, evidence of levels of exposures and effects on morbidity in the field is very limited. There have been calls for toxicological studies to take into account natural background concentrations of particles and focus on exposure levels that bear some relation to real environmental concentrations, and for a structured approach to the testing of different properties to identify which are the most relevant drivers of microplastic toxicity (Lenz *et al*.2016; Koelmans *et al.* 2017).

Microplastics have been reviewed by the EU's SAPEA (2018), and featured in the 2018 list of emerging health and environmental issues by SCHEER (2018). Both conclude that there is a need for a better assessment of hazard and risk[43], and two relevant projects under Horizon 2020 have been proposed[44].

Regarding risks to human health, several reviews (e.g. GESAMP, 2016; Wright and Kelly, 2017; Revel *et al.*, 2018; Rist *et al.*, 2018) have pointed to the presence of microplastics in food destined for human consumption. In laboratory studies, microplastics may be expected from general medical research to have the potential to trigger allergic reactions, asthma, lesions, cancer or heart disease, as well as the possibility for chemical toxicity from monomers, additives or adsorbed environmental pollutants. Evidence on which to base a risk assessment is currently lacking, but the potential effects on human health remain a concern (Vethaak and Leslie, 2016).

However, the basic toxicological approach of comparing concentrations between laboratory tests and those encountered in the environment only addresses one aspect of the issue. The ubiquitous nature and extreme persistence of plastics, the inability to retrieve them once they have entered the environment, the inevitability of ingestion and transfer up the food chain, the combination of potential effects that cannot be simulated in the laboratory, and the continued rapid growth in the extent of contamination raise issues that cannot be addressed by standard risk analysis (Backhaus and Wagner, 2018). Such factors are particularly important in influencing public perceptions and driving calls such as from UNEP to rid the oceans of macroplastics and microplastics through measures to promote reduction of plastic use, waste recycling and disposal facilities (see section 8.10).

A2.2 Plastics and the terrestrial and freshwater environment

While much public attention has focused on marine environments, the vast majority of marine pollution originates from land; consequently, the amounts of plastic on land are considerably higher (some 4–23 times) (Horton *et al.*, 2017; Machado *et al.*, 2018; Horton and Dixon, 2018). Even more than is the case with marine plastics, reviews (e.g. Royal Society, 2019) find a dearth of information on the effects of plastics of different plastic sizes on land and in freshwater. Potential adverse effects can be physical through ingestion of different sizes by birds, mammals and other organisms, and may (either directly or by adsorption of other contaminants) exert toxic effects (see Anderson *et al.*, 2018; Machado *et al.*, 2018). Some of the evidence of effects at different scales is summarised in Machado *et al.*, 2018, as shown in Figure A2.4.

Sources of microplastics, in addition to the general leakage of plastic packaging, include the following.

- Microplastics in sewage sludge (Nizzetto *et al.*, 2016 estimated that annual additions of microplastics to agricultural land from urban sources including sewage sludge were between 125 and 850 tonnes of microplastics per million inhabitants; this is equivalent to an annual input of 63,000–430,000 tonnes across Europe).
- Microplastics in composted domestic and industrial waste which are applied as soil conditioners (since most of the bio-waste collected from households and industry contains plastics (Weithmann *et al.*, 2018)).
- Residues from controlled release fertilisers (where the plastic pellet in which the fertilisers are contained, persist in the soil).
- Agricultural plastic mulches (around 100,000 tonnes per year in the EU (SWD/2016/64 final)).
- Discarded plastics from greenhouses.

Studies reviewed in Horton *et al.* (2017), Machado *et al.* (2018) and others have indicated some impacts that have been observed in the field, but many more potential impacts cannot yet be assessed owing to

[43] SCHEER considered that the 'standardisation of methods for assessing exposure, as well as the development of methods for assessing the different behaviour in living organisms of micro and nano plastics, represent urgent priorities'.
[44] CE-SC5-29-2020: a common European framework to harmonise procedures for plastics pollution monitoring and assessments; CE-SC5-30-2020: Plastics in the environment: understanding the sources, transport and distribution of plastics pollution.

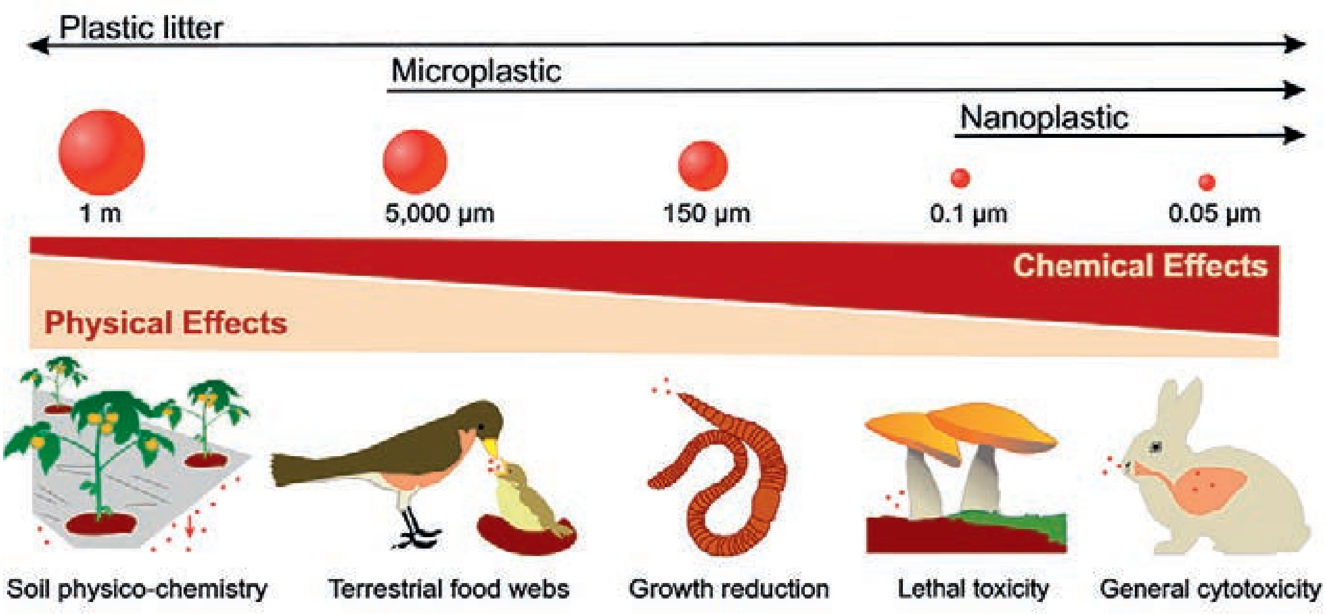

Figure A2.4 Range of potential impacts of plastics contamination of different sizes (Machado et al., 2018). Specific effects referenced are: soil biogeochemistry (Steinmetz et al., 2016); ingestion by birds (Gil-Delgado et al., 2017; Holland et al., 2016; Zhao et al., 2016); reduction in growth of earthworms (Lwanga et al., 2016); lethal toxicity to fungi (Miyazaki et al., 2014, 2015); mammal lung inflammation (Hamoir et al., 2003; Schmid and Stoeger, 2016) and broad cytotoxicity (Forte et al., 2016) of nanoplastics.

the limited amount of work done in the terrestrial and freshwater environments so far. For instance, studies have shown how accumulation of microplastics in soils can reach levels that change the biophysical environment and affect soil function. For instance, effects on earthworms are not only on individuals but extend to soil structures related to nutrient cycling and aeration (Lwanga *et al.*, 2016). The presence of additives with endocrine-disrupting properties, other chemicals and effects of plastic particulates has been suggested as potentially affecting agricultural productivity (Steinmetz *et al.*, 2016).

Similar mechanisms found in the marine environment can also be expected in aquatic and terrestrial environments: large plastics cause organism entanglement while smaller particles can be ingested or inhaled, blocking the digestive tract, or abrading and irritating mucosa. Contamination in living organisms is already widespread: for instance, Zhao *et al.* (2016) found microplastic present in the digestive tract of 94% of dead terrestrial birds with diverse foraging behaviour in China.

Potential chemical effects could result from the leaching of plastic additives, plasticisers, etc. For instance, phthalates, bisphenol and many other plastic additives have been found at moderately high levels in potentially microplastic-rich sludge from water treatments used for agricultural purposes. Reviewers such as Machado *et al.* (2018) and Royal Society (2019) thus conclude that there is a need to prioritise research related to fate and potential effects of microplastics in terrestrial ecosystems. In addition to a need to understand the distribution of microplastics in terrestrial environments and transport, degradation and disintegration processes, the potential of microplastics to physically and chemically disrupt physiologically important functions is poorly understood, together with any resulting effects at the community or ecosystem levels. As cellular and subcellular effects of nanoplastics have been shown in the laboratory, the transport to other parts of the body also remains to be analysed.

Abbreviations

DRS	Deposit–return scheme
EASAC	European Academies' Science Advisory Council
EC	European Commission
EIA	Environmental Investigation Agency
EMF	Ellen MacArthur Foundation
EPR	Extended producer responsibility
EPS	Extended polystyrene
EU	European Union
GESAMP	Joint Group of Experts on the Scientific Aspects of Marine Environment Protection
GHG	Greenhouse gas
HDPE	High-density polyethylene
IEEP	Institute for European Environmental Policy
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IUPAC	International Union of Pure and Applied Chemistry
JRC	Joint Research Centre (EU)
LCA	Life cycle assessment
LDPE	Low-density polyethylene
MBI	Market-based instrument
MMT	Million metric tonnes
NAO	National Audit Office (UK Parliament)
NIR	Near infrared
OECD	Organisation for Economic Co-operation and Development
PBS	Polybutylene succinate
PE	Polyethylene
PET	Polyethylene terephthalate
PHA	Polyhydroxyalkanoates
PHB	Polyhydroxy butyrate
PLA	Polylactides
PP	Polypropylene
PRO	Producer responsibility organisation
PS	Polystyrene
PVC	Polyvinyl chloride
RECOUP	RECycling Of Used Plastics
SAPEA	Science Advice for Policy by European Academies
SCHEER	Scientific Committee on Health, Environmental and Emerging Risks
SUP	Single-use plastics
UNEP	United Nations Environment Programme
WRAP	Waste and Resources Action Programme

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