Sustainable Plastics – the role of chemistry

Summary of a roundtable discussion meeting hosted by the RSC Materials Chemistry Division
1 March 2019, London

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Executive summary

This short report represents the output of a roundtable discussion meeting hosted by the Royal Society of Chemistry's Materials Chemistry Division, on the topic of sustainable plastics. In the context of growing calls from scientists, policymakers, and the wider public, to address the challenges of plastic waste and sustainability, the meeting addressed the question of what chemical scientists can do to tackle the problem.

The core messages of the discussion were:

- Plastics are complex composite materials comprising polymers and additives, and approaches to deal with plastic waste must address both.
- Plastics have many useful properties and are often the most environmentally friendly choice. We must address the harmful effect of plastic waste in the environment, balanced against the need to retain the properties and applications that society needs.
- Chemists will play an important role in providing solutions to immediate challenges, as well as through fundamental research over longer timescales to deliver transformative changes in our relationship with plastic materials.
- Bio-derived and biodegradable plastics will play a role in addressing the challenges. However, they should not be used to legitimise a throwaway culture.
- It is important to distinguish between polymers which are bio-sourced (and not biodegradable) and those which will biodegrade safely in the natural environment. It is crucial to develop the right standards for bio-derived and biodegradable plastics, based on their true environmental impact.
- Plastic waste is a systems problem, influenced not only by science, but by economics, policy, and consumer behaviour. Solutions must address all these factors and not treat each in isolation.
- At all stages, decisions should consider the overall environmental impacts of a course of action. Lifecycle analysis is a vital tool to enable this evidence-based decision-making.
- There is significant strength in the UK chemical sciences research community, with the skills and expertise to address the challenge of plastic waste. Bringing this community together, across academia, industry and government, and through working with international partners, will help to accelerate change through collaboration.

Audiences for this report

- Funders and representatives of funding bodies. The conclusions represent a chemistry community viewpoint of key scientific questions that remain unanswered and will require sustained research effort to solve the issues presented by single use plastics.
- Chemical scientists and the wider scientific community, to stimulate discussion around the priorities for chemical sciences research.
- Policy and decision makers to understand where the science exists to underpin policy decisions and where there are evidence gaps.
- The report will also inform wider RSC indicatives in sustainability and sustainable plastics.

Introduction

There is currently increased interest in the environmental impact of plastics from the media, the public and from policymakers. A number of policy initiatives have been implemented, for example the European Union Strategy for Plastics in a Circular Economy, and the UK Government's Waste and Resources Strategy for England. Many companies, charities and individuals are making commitments to reduce or eliminate plastic packaging. In parallel, scientists are working to develop new types of plastic and polymeric material, as well as methods for recycling plastics, both to reduce their environmental impact, and to ensure that they remain in the economy for longer.

Given this rapidly evolving context, the RSC Materials Chemistry Division hosted a roundtable discussion meeting on 1 March 2019, bringing together stakeholders from across the chemical sciences research community to contribute their views on the future for sustainable plastics, and on the contribution that the chemical sciences will make.

The group, including academic experts in polymer science, sustainable chemistry, and the impacts of plastics on the environment, discussed the challenge of single use plastics, the policy and economic context, and the research questions that chemists need to address in order to provide solutions.

What are plastics?

The term "plastics" is frequently used in discussions of the topic to refer to a large category of materials. Finding the right solutions depends on our understanding of the different types of material within the category of "plastics", as the solutions will differ depending on the chemical composition of the material.

Plastics are complex composite materials, combining polymers with additives (including plasticisers, dyes, fire retardants, or antioxidants) to confer specific properties. Polymers commonly used in plastic packaging and in other applications include polyethylene (PE), polypropylene (PP), poly(ethylene terephthalate) (PET), polyester, Nylon, polyvinyl chloride (PVC) and polyurethane.

Beyond packaging, plastics and polymers are also used in construction, vehicle manufacture, fishing, agriculture, clothing, medical products and consumer goods. Since their discovery a century ago, plastics and polymers have become ubiquitous and integral to our everyday lives.

As a result of their properties of lightness, strength, versatility, low toxicity and low cost, they have delivered improvements in medical technology and food handling, as well as reducing carbon emissions for transportation due to their light weight. However, the properties that make plastics so useful, particularly their low price and durability, have led to an explosion in the amount of plastic that we use, and to the significant problem caused by plastic waste in the environment.

The environmental challenge

There is growing recognition of plastic waste as a major pollutant in the natural environment. The ubiquity of plastics across all areas of human activity, as well as their low cost, means that there is little incentive to capture and reuse or recycle plastic waste.

The damage that can be caused when plastics reach the environment include the effect of large plastic items ingested by marine animals and seabirds, and the pollution of water, land and air by micro- and nano-plastics. These are either released directly, for example microbeads from cosmetics or microfibres from washing synthetic fabrics, or may arise through breakdown of larger plastic objects in the natural environment through erosion. Other environmental impacts which have been documented include the leaching of toxic substances from plastics (for example, additives) which can have endocrine disrupting impacts on aquatic organisms, and the ability of some plastics to absorb harmful substances from the environment and cause them to enter the food chain.

Chemistry will play a significant role in understanding, quantifying and mitigating the environmental impact of plastics. This includes analytical methods and environmental forensics to detect and measure plastic pollution, as well as methods to remove plastic and microplastic waste from the environment, or break it down in situ to non-harmful products.

Bioplastics

The materials used to make plastics are largely derived from fossil resources, primarily oil and gas. Current estimates indicate that around 4-8% of the world's oil production is used in plastics manufacture[1, 2] (while almost 90% of oil and gas is used in electricity production, heating or transport[2]). There has recently been a significant increase in the use of plant-based raw materials to make so called "bio-plastics". These include polymers made by directly replacing of fossil-derived monomers for those from plants (for example in bio-PET, used to make drinks bottles), as well as alternative polymers such as poly-lactic acid (PLA), produced from fermented sugars.

It is important to note that plastics derived from renewable bio-resources are not necessarily more environmentally benign than plastics from fossil sources. These polymers may not be biodegradable, and can persist in the natural environment in the same way as a conventional polymer. There is also evidence that, regardless of whether the polymer is biodegradable or not, the environmental impact of many bioplastics can be more damaging than the fossil equivalent[3]. This can be as a result of the impacts on land and water use in growing bio-feedstocks, or through higher CO_2 emissions from processing the feedstocks into useable monomers.

It will be important to consider environmental standards for bioplastics, to ensure that the production and use of these polymers does not cause greater environmental damage than the products they replace. As discussed on page 10, life cycle assessment of different materials and options is crucial in making evidence-based decisions that will protect the environment.

The policy context

In January 2018, the European Commission adopted a Europe-wide strategy on plastics[4], as part of the transition towards a more circular economy. It is aimed at protecting the environment from plastic pollution whilst fostering growth and innovation. The strategy envisages the founding of a new plastic economy, where the design and production fully respect reuse, repair and recycling needs and more sustainable materials are developed. Under the new plans, all plastic packaging on the EU market will be recyclable by 2030, the consumption of single-use plastics will be reduced and the intentional use of microplastics will be restricted.

HM Government's 25 Year Environment Plan[5] sets out a strategy to ensure that resources are used more efficiently, and kept in use for longer to minimise waste and reduce environmental impacts. The Plan includes targets to work towards zero avoidable waste by 2050 and eliminate avoidable plastic waste by end of 2042 by taking action at each stage of the product lifecycle – production,

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[1] World Economics Forum (2016), The New Plastics Economy – Rethinking the Future of Plastics

[2] Plastics Europe (2016), Plastics – the Facts 2016

[3] Chen et al, Comparative life cycle assessment of fossil and bio-based polyethylene terephthalate (PET) bottles. *Journal of Cleaner Production*, 2016; 137: 667

[4] European Commission (2018), A European Strategy for Plastics in a Circular Economy

[5] Department for Environment, Food & Rural Affairs (2018), A Green Future: Our 25 Year Plan to Improve the Environment

consumption, end of use and end of life stages. In addition, it aims to significantly reduce and where possible prevent marine plastic pollution, in particular material that came originally from land.

The UK Bioeconomy Strategy (2018)[6] makes provision for producing smarter, cheaper materials such as bio-based plastics and composites for everyday items as part of a more circular, low-carbon economy, and to reduce plastic waste and pollution by developing a new generation of advanced and environmentally sustainable plastics, such as bio-based and biodegradable packaging and bags.

The Resources and Waste Strategy for England (2018)[7] highlights several proposed initiatives for dealing with plastic waste, ranging from unified household collections to funding for research into alternatives to plastic packaging. The Government also intends to bring forward a requirement that all packaging entering the UK market should contain a minimum of 30% recycled content by 2025. As a part of the strategy, Defra will issue a series of consultations on future waste management, including a consultation on standards for bioplastics, to develop evidence on what makes a good product standard in this space. It is important that scientists engage with this process, and present the science to policymakers in a way that they can use to inform decision-making.

The International Maritime Organisation (IMO) Marine Environment Protection Committee (MEPC) adopted an action plan in 2018 to address maritime plastic litter from ships. This aims to strengthen existing regulations within the International Convention for the Prevention of Pollution from Shops (MARPOL) and support new measures to reduce littering.

Funding initiatives

The Plastics Research and Innovation Fund (PRIF) is a £20M fund coordinated by UKRI to support *new ideas and innovations to bring changes in the UK's plastics manufacturing and consumption patterns*. The fund supports The UK Circular Plastics Network (to enable networking and knowledge exchange), an £8M programme of support for creative approaches to a circular economy in plastics waste, as well as £10M for business led R&D, through Innovate UK.

A further £60M for Smart and Sustainable Plastic Packaging has also been announced as part of the Government's Industrial Strategy Challenge Fund (subject to business case approval and match funding from industry). This includes research on new plastic materials as well as smart labelling to reduce food waste.

The UK Microplastics Network is funded by NERC to support knowledge exchange and collaboration the topic of microplastics.

Other major initiatives include the £1.4M UK Circular Plastics Flagship Projects Competition, organised by WRAP (the UK Waste and Resources Action Programme) and the Ellen MacArthur Foundation.

RSC activities

The RSC is working with the scientific community, policy makers, government, industry and other stakeholders to share knowledge on the challenges and solutions to the plastics pollution problem, both to protect the environment and to ensure that plastic retains its value within our economy for longer. Recent initiatives in this field include:

- In 2017, the RSC's ESED division and Water Science Forum (WSF) held a one-day workshop at Burlington House entitled *Microplastic pollution – everyone's problem but what can be done*

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[6] Department for Business, Energy and Industrial Strategy (2018), Growing the Bioeconomy
[7] Department for Environment, Food & Rural Affairs (2018), Our waste, our resources: a strategy for England

[*about it?*](#) The UK Microplastics Network and WSF have held further meetings to advance the science in this field, including a workshop in 2018 on Microplastic Methods.

- The RSC submitted a response to the consultation on Environmental Protection (Microbeads) (England) Regulations 2017 and submitted written evidence in April 2016 to the Environmental Audit Committee inquiry on the Environmental Impacts of Microplastics.
- As part of the British Science Association's Huxley Summit in November 2018, we used our Facebook channel to live-stream a round-table discussion entitled "Single-use plastics – what are the issues and what are the solutions?"
- The RSC's Synergy Programme is a collaborative programme with industry, bringing together large companies in a range of industry sectors to develop a future roadmap for a circular economy in polymers in liquid formulations (for example those polymers found in paints, lubricants, or personal care products). The programme has held workshops to identify opportunities for innovation and collaboration.

Economic drivers

Industry will play an important role in driving forward any changes in the way in which we use plastics and polymers. Industry initiatives in sustainable polymers stem from different motivations. Some companies may want to offer greener products to gain competitive advantage, others are looking for new polymers to use in applications such as electric cars. Others are looking to reduce dependence on fossil feedstocks, for example by using degradable and recyclable alternatives in their polymer product ranges.

When considering bringing new materials to the market, it is important to acknowledge that these new materials must be compatible with existing recycling infrastructure and not introduce contamination. It is also important to ensure that alternatives and solutions are truly more sustainable on a lifecycle basis, with the evidence to back up claims of sustainability. The need for robust and comprehensive life-cycle modelling of environmental impacts, which can help drive decisions around materials choices and consumer behaviour, is discussed further on page 10.

Recycling infrastructures at local authority level must contend with other funding pressures and may need to demonstrate profitability in order to be built at all. Governments at a national and local level should work together to ensure that the responsibility for dealing with plastic waste is accompanied by sufficient funding to build and maintain recycling facilities.

There are also systems-level economic considerations in establishing new types of collection. For example a deposit return scheme of reusable bottles needs sufficient inventory and physical storage space to be successful, and there need to be the right incentives, legislation and policies to adapt to a refill society. The plastic bag charge is a good example of driving consumer behaviour through nudges and financial incentives.

Although the challenges are great, there is a good analogy with the energy sector and how it has moved towards an energy mix. There is an opportunity for the UK to develop new industrial and manufacturing capability based on sustainable materials.

The role of chemistry

Chemistry has a role to play at all levels of the waste hierarchy, from reducing the amount of plastic used, to promoting safe and environmentally benign degradation of plastics at the end of their life.

Discussion participants developed a list of challenge areas that chemistry can help to address. These are classified according to what we can do today (Immediate Priorities), and the fundamental research that will be needed to enable a step change over a longer timescale, and could kick-start new manufacturing in the UK. We have drawn together the outcome of these discussions into four categories (Reduce, Reuse, Recycle and Degrade) as well as highlighting system-level challenges that related to all stages of the waste hierarchy.

Delivering impact on both short and long timescales will require working together with industry to achieve practical deployment, particularly at the scale required to make an impact. There may be opportunities to do so via the project partners in PRIF-funded research.

Other challenges identified during the workshop are shown in Appendix 1.

Reduce the number of plastics in a single product

A strong theme throughout the discussion was the need to simplify products to support recyclability. This is particularly true for multi-material packaging, where a single piece of packaging is made from many different plastics. Reducing the number of polymers in any one product would help to mitigate this, as well as ensuring that new materials which are introduced have clear routes to recycling and degradation, and do not compromise existing recycling systems. Finally, there is a case for restricting use of those plastics which are most difficult to recycle or dispose of, such as PVC or expanded polystyrene.

Reuse plastics more effectively

- ### Markers and labelling

Effective reuse and recycling depends on having a good understanding of material content and provenance. This requires us to have effective measurement techniques and standards in place to assess the composition of a plastic material (for example, to identify the level of recycled polymer content), in order to understand how they can be recycled and reused. Work in this field has developed metrics for bio-based content[8], but there is work to do in developing effective metrics for assessing content which is recycled or produced from waste carbon dioxide.

Chemistry can develop chemical or spectroscopic labelling for polymer materials. These markers, incorporated in a product, could be used to provide information on material provenance and content. Markers and labels would also support the recycling theme by giving indicators of the appropriate recycling processes for each material, including those which have reached the natural environment as fragments.

Recycle plastics more efficiently

- ### Overcoming the thermodynamics of polymer mixing, to enable recycling of mixed polymer waste

Some types of plastic (for example polyethylene, polypropylene and PET) can be individually recycled through melting and reforming into new products. However, recycling of mixed wastes, for example from household collections, is extremely difficult due to the underlying thermodynamics of polymer mixing, as described by the Flory-Huggins equation. This dictates that in many cases, mixtures will separate out into phases (due to the low entropy of mixing), with the resulting material unsuitable for use in new plastic products.

[8] Clark, James Hanley, Farmer, Thomas James and Sherwood, James Richard (2015) Assessment study report of indirect declaration techniques to determine total bio-based content. Report. KBBPPS

Chemistry can develop new materials, such as co-polymers, which can promote mixing of unlike polymers through interactions with both polymer components at the interface between them.[9]

- Understanding and optimising the kinetics of the back reaction

Polymerisation chemistry is optimised with respect to the 'forward' reaction, that is, the polymerisation reaction that takes monomers and converts them into long chains. We understand very well how to optimise this reaction to achieve fast and controllable polymerisation. The reaction is an equilibrium and in principle can be reversed, but we have very little knowledge of how to do this efficiently and enable easy depolymerisation. This (uniquely chemical) insight could deliver substantial advances in technology to break polymers apart.

Chemistry can improve our knowledge and understanding of the kinetics of depolymerisation (i.e. the 'back reaction') and how to promote it. This could result in a low temperature and efficient method to disassemble polymers, which would allow recycled monomers to compete with new 'virgin' feedstock from fossil sources. Chemistry will also develop monomers and catalysts that promote depolymerisation.

- Dealing with additives and contaminants

The term 'plastics' is often used interchangeably with 'polymers', but in reality most plastics are composite materials formed from polymers and a range of additives. These additives include plasticisers, dyes, stabilisers, antioxidants and flame retardants. Plastic materials may also include contaminants as a result of improper cleaning, staining or absorption of substances from the environment, as well as legacy materials which have been phased out of plastic production but may still exist in older plastic products.

Additives and contaminants can cause major issues in polymer recycling, including:

- safety issues, for example if contaminants, legacy materials or unknown substances are incorporated into recycled plastics, this may prohibit their re-use in food packaging or consumer goods
- problems for chemical recycling processes, for example some additives may not be compatible with the pyrolysis or cracking processes that are used to return polymers to useable monomers
- environmental hazards resulting from reuse and waste disposal
- aesthetic considerations, for example, if coloured and transparent plastic are melted together, the resulting product cannot be used to make transparent products any longer

Chemistry can develop methods for separation of additives, as well as developing new additives that are compatible with recycling technologies such as chemical cracking or pyrolysis.

- Learning from nature

Nature effectively recycles materials for repeated reuse, for example breaking down and recycling proteins via their constituent amino acids. Recent reports have also demonstrated the potential role of bacteria and microorganisms that can promote breakdown of plastics through the action of enzymes (biological catalysts). Learning more about the mechanisms and processes that nature uses to break materials down, can lead to new discoveries and new materials.

Chemistry can learn from nature and design new materials which can be more effectively recycled, as well as to develop processes based on photocatalysis or enzyme catalysis, which can break

[9] For example, Eagan, James M et al (2017), Combining polyethylene and polypropylene: Enhanced performance with PE/iPP multiblock polymers, Science 355, 6327

down plastics. Synthetic biology may also have a role to play in developing these materials and methods.

Degrade plastics safely

- ### How does degradation work and how can it be induced?

Our understanding of polymer degradation under various environmental conditions is still very limited. This includes the degradation of 'conventional' plastics such as polyethylene, as well as polymers that are designed to biodegrade. At a fundamental level, there is also a need to improve our understanding of how to break carbon-carbon bonds. Some work is already being done in this space, both to understand degradation pathways of biodegradable polymer molecules, as well as to develop a baseline understanding of how 'traditional' plastics break down in the environment to form microplastics[10].

Chemistry can elucidate the mechanisms of degradation of polymers in the natural environment. This work may also require collaboration with biological scientists to understand the impact of polymer degradation products on the natural environment. This includes their climate impact, potential toxicity, and the impacts on ecosystems of access to new food sources. There is also an opportunity to develop new methods for breaking down polymers.

Understand the problem as a system

- ### Energy inputs and overall environmental impact - the importance of life cycle analysis

The environmental impact of any material or process must include a full lifecycle consideration. This includes the end of life impact of waste, as well as the energy inputs, impacts on water or land use, CO_2 emissions from production, use, and transport, and the impacts of any by-products. A complete picture must also take into account the energy sources used to process and manufacture products (for example comparing the environmental impact when energy for production is derived from CO_2-emitting fossil fuels, compared to nuclear or solar power), as well as whether an item is reusable or single-use. Comparisons of plastic with other materials should also consider the impacts on transport CO_2 emissions, which may be lower for plastics as a consequence of their light weight, and the potential impact on product shelf life, as in the case of food packaging.

Lifecycle analysis (LCA) could provide an objective way to understand the impacts of different materials and allow evidence-informed decision making around the most sustainable choices.

In many cases, lifecycle analysis has shown that plastics packaging can be the most sustainable choice, particularly when factors such as CO_2 emissions are taken into account. For example, studies of bioplastics, renewable feedstocks and chemical recycling processes have indicated that on a lifecycle basis, these alternatives may be more harmful to the environment than the production of plastics from fossil resources[11]. A further example is given by a study published in 2011, which estimated that a cotton shopping bag had the equivalent global warming impact of over 170 single-use plastic bags[12]. Further studies are needed in order to assess the full lifecycle impact of different material choices (including the impact of waste materials at the end of their life), to support sustainable decision making by manufacturers, product designers, and consumers.

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[10] Gewert, B et al, Pathways for degradation of plastic polymers floating in the marine environment. *Environmental Science, Processes & Impacts*, 2015; 17, 1315-1521

[11] Chen et al, Comparative life cycle assessment of fossil and bio-based polyethylene terephthalate (PET) bottles. *Journal of Cleaner Production*, 2016; 137: 667

[12] Edwards and Meyhoff Fry J (2011), *Life cycle assessment of supermarket carrier bags: a review of the bags available in 2006*, Environment Agency.

The development of 'LCA-as-a-service' could help researchers and industry to move forward and develop solutions. There are many challenges in developing LCA methodologies, and while standards do exist, there is significant debate in the field. A critical problem in conducting lifecycle analysis at scale, is that many of the data inputs do not scale linearly, so it is challenging to draw conclusions from small-scale studies.

Chemistry can develop robust and appropriate LCA methodologies to support making sustainable choices. Chemists should take the opportunity to engage with life cycle analysis as a tool to aid decision making.

- ### Scaling up

Solving the plastics waste crisis requires a deep understanding of the scale of the challenge, and the development of solutions that will deliver at scale to truly make a difference. We need to increase recycling collections, as well as developing recycling methods that are cost effective and require lower energy input. Delivering sustainability at scale may also require us to make increased use of polymers in new application areas, in place of other materials. For example, replacing concrete with plastics in some applications may lead to an overall reduction in the environmental impact of construction, through a reduction in the lifecycle carbon emissions of manufacturing.

Chemistry, working hand in hand with chemical and process engineering, can develop scaled up methods to deliver the manufacture and recycling processes needed to address the challenges of plastic waste.

Education

Plastics are closely tied up with our economy and consumer behaviour, and chemical education is an important part of encouraging changes in behaviour. The RSC can play a role in helping people to understand what polymers and plastics actually are, and how they can be recycled. Education and public awareness campaigns about plastics and plastics recycling could include measures to highlight 'hidden' plastics which consumers may be unaware of (for example in wet wipes), and information about how plastics can be recycled, encouraging improved take up of these systems. There is a need to dispel misinformation about particular types of packaging (for example perceptions around recyclability or environmental impact of different packaging types), based on accurate scientific evidence.

It can also encourage sustainable choices by consumers and thereby trigger corporate changes via consumer demand and shareholder pressure. This will also promote corporate responsibility and the introduction of ethical business practices throughout the plastics value chain.

Core messages and recommendations

Plastics are ubiquitous in our global economy and have revolutionised many areas of life since their discovery a century ago. They have many desirable properties and in many cases are the most environmentally friendly choice. At the same time, plastic waste has major environmental impacts on the natural environment. We need to balance these environmental risks against the substantial benefits that plastics bring.

The problem of plastic waste is a system-level problem and requires input from stakeholders in research & innovation, industry, policy and the wider public if we are to solve it. There is no single approach to the problem and no one-size-fits-all solution. Decisions should be led by sound science and good quality evidence, to ensure that the measures will truly tackle the problem at the scale required, and will not introduce undesirable consequences (such as increased CO_2 emissions). As such, burning plastics for energy should be a solution of last resort.

There is a significant strength in the UK research community in polymer science, which is recognised across the world. There are also opportunities, and a pressing need, to collaborate internationally, including with countries in Southeast Asia which have the highest burden of plastic waste. Funding mechanisms for international collaboration are important to support this work (for example, the Global Challenges Research Fund, subject to project compliance with Official Development Assistance guidelines).

Through engaging with industry, and with other expert stakeholder groups across the sciences, chemists can help kick-start a second industrial revolution based on sustainable resources.

We need:

- Further investment for research & innovation to answer the immediate and pressing challenges of plastic waste, as well as longer term research to lay the foundations for more sustainable usage of materials. This includes innovations in polymer chemistry and plastics recycling, as well as rapid, routine, low cost analytical techniques for routine monitoring of water supplies, beverages and foodstuffs.
- Development of standards for recyclability of plastics, evidence-led standards for bioplastics and biodegradable materials, and increased demands for recycled plastic content in new products.
- Information on manufacture, material flows, fate and effects of plastics, including nanoplastics.
- Monitoring and enforcement of waste regulations to maintain and improve our environmental performance including policies to reduce the use of avoidable plastic waste e.g. in packaging.
- Evidence to help support policy measures which make recycling and reuse easy, and to drive down usage of the most harmful types of plastic. This includes deposit return schemes, restricting use of hard-to-recycle plastics (such as black plastics), standardising packaging and labelling across consumer products to align with recycling processes, and expanding financial incentives and penalties such as the plastic bag charge.
- Education and public awareness campaigns about plastics and plastics recycling. This could include measures to highlight ‘hidden’ plastics which consumers may be unaware of, and information about how plastics can be recycled, encouraging improved take up of these systems.

Appendix 1 – Research and policy challenges

This table summarises a set of ideas noted during the workshop session. It is not an exhaustive list.

REDUCE plastic usage Immediate priorities • “Nudge” policy measures to drive societal change • Reduce tendency to over-engineer packaging, working with big global users companies, and packaging designers • Understand the trade-offs between light-weighting and recycling, since lightweight packaging is often difficult or expensive to reprocess Long term • Reduce the number of different plastics in use, optimising a smaller set of polymers for specific applications	REUSE plastics more effectively Immediate priorities • Develop technology for separation of lamellar materials, multi-layered packaging, and composites, so that materials can be reused • Chemistry to inhibit the degradation of performance as plastics age • Incorporate labelling via chemical or spectroscopic markers to trace material provenance, assign responsibility for waste, and provide information on how to correctly recycle • Improve surface chemistry of materials Long term • Explore vitrimer chemistry to develop new materials that can be used in place of thermosets • Design materials for long-term use/reuse
RECYCLE plastics through mechanical or chemical means Immediate priorities • Redesign additives to aid compatibility with recycling processes • Ban hard-to-recycle plastics (for example, black single use plastics) • Recycling chemistry that operates economically, at scale, with low CO_2 impact • Identify application areas beyond packaging, where new recycling chemistry is needed • Encourage consumers to view recycled materials as of equivalent quality • Chemically compatibilise waste streams, for example through interfacial agents to aid polymer mixing • Optimise recycle processes for simple uses – e.g. bitumen for roads Long term • Research on the retro-reaction for polymerisation • Reduce the range of polymers used, and simplify products where possible • Biomimetic and synthetic biology approaches to recycle materials • Recycling polymers used in high-tech applications (for example molecular electronics)	DEGRADE plastics safely at end of life Immediate priorities • Better quantify and standardize biodegradable (compostable) polymers. For example, differentiating truly biodegradable polymers from compostable products that degrade to form microplastics • Understanding the fate of polymers in the specific environment where they are released (air, water, or land) • Use processes from chemical recycling where possible, to safely degrade polymers in situ Long term • Research on the retro-reaction for polymerisation • Develop degradable monomers based on synthetic biology and bio-derived materials such as algae or lignin, and new monomers repurposed from polymer degradation products

All areas should be underpinned by effective regulation and collaboration with industry

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