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

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 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 bioconsumption, 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.

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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 roundresearch 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

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

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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 lifecycle analysis

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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

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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.

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-

Acknowledgements

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