UNIVERSITY OF BIRMINGHAM

PLASTIC

A CALL TO ACTION

Plastic pollution poses a threat to humanity which could be on a similar scale to climate change. In order to combat this, we cannot continue to simply manage plastic; we must fundamentally reimagine it.

The Birmingham Plastics Network

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EXECUTIVE SUMMARY

The world has produced over 10 billion tonnes of plastic,[1] and thrown away almost 8 billion.[2]

Given the known risks to human, animal and environmental health, and the gaps in our knowledge, plastic pollution could prove as existential a threat to humanity as climate change. If so, it is not enough to simply manage plastic; we must fundamentally reimagine it.

History strongly suggests that a sustainable solution to plastic will not emerge without co-ordinated, multi-stakeholder, multi-disciplinary engagement by all those with a vested interest in plastic across its value chain. There is an urgent need to reimagine our relationship with plastic and this call to action looks to set in motion an innovative approach to future policy and innovation regarding a sustainable solution to plastic. This is driven by the following top-level concerns about the ways in which environmental and social concerns surrounding plastic are currently being perceived or addressed:

- The responsibility for who addresses (and benefits from) the plastic problem is poorly understood and often disputed.
- The cost of plastic does not reflect its full environmental cost, nor does it reflect the value plastic contributes to society.
- Replacing or reducing plastic usage needs to be done in such a way that both addresses, but also conversely does not increase, the risk of harm to the environment, social equity and health and well-being.
- There are significant gaps in our understanding of the downstream impacts and implications of plastic production, usage and disposal.
- Many initiatives tend to focus on one type of plastic production or usage. It is vital to tackle all plastic, not just the most visible usages (e.g., consumer packaging).
- Many past solutions to the plastic problem have inadvertently made things worse and, due to a lack of engagement with key stakeholders and limited interdisciplinary research in this domain, there is a risk that the solutions of today may well do the same.
- There is misleading messaging or greenwashing around key terms, e.g. ‘biodegradable’, ‘bioplastic’, ‘zero-plastic’ and ‘compostable’.
- There is a strong public desire to address the plastic problem, but our recent UK survey suggests there is a mismatch between public expectations of how plastic should be produced, labelled and disposed of, and the realities of what is currently being implemented or prioritised.
- Science, business, policy makers and communities have parts of the solution, but no-one seems to be connecting all the dots.

It is vital to adopt a whole systems approach to understanding the complex intersecting issues surrounding plastics, in order to better inform the ways in which we produce, use and dispose of them.

Furthermore, we need to understand where the responsibility lies for all the avoidable costs and impacts of plastic, and engage all stakeholders if we are to have any chance of producing and using plastic sustainably. Currently, knowledge of the complex intersections between plastic and key socio-ecological systems is too fragmented for informed decision making.

The recommended forward strategy outlined in this report, led by the Birmingham Plastics Network, will move beyond the fragmented, siloed solutions promoted by those with vested interests, by creating an interdisciplinary, science-based and inclusive process that will examine the possibility of solutions that optimise the sustainable potential of plastic.

INTRODUCTION

If we were to invent plastic today, we would probably not start from here. In an ideal world, plastics would perform their functions at reasonable energy and financial cost; emit little or no CO_2 during their entire lifecycle; inflict no health or environmental damage if they escaped into the environment; and be capable of sustainable recycling at the end of their useful lives. In other words, we would enjoy all the benefits and none of the damage of today's plastic; in turn, plastic would be compatible with the UN's Sustainable Development Goals (SDGs). However, due to the ways that plastics have been developed, marketed, and utilised over the past century, there is a sustainable plastic gap that urgently needs addressing. Imagine if it were possible to completely readdress the balance when it comes to plastic production, usage, and end of life.

What if it were possible to:

- Capture and infinitely recycle and reuse all plastic waste?
- Have renewable plastic feedstocks that have a lower carbon footprint?
- Have plastic which degrades naturally in a short period of time, into materials that contribute to regeneration and enhancement of natural systems?
- Cost plastic in a way which fully reflects its entire life cycle – including social, economic and environmental impacts?
- Value plastic by recognising its value to society?
- Only use plastic when no other material would suffice?

At present, the ways in which we are addressing the plastic problem are fragmented. Some pathways to possible solutions exist, but these are often developed in silos privileging vested interests. Moreover, whilst some of the best solutions currently being proposed are well-meaning, they push problems down the road or pass on costs inequitably. Meanwhile, some of the worst solutions being put forward are green-washing attempts to perpetuate business as usual. Currently, our position is that knowledge of the complex intersections between plastic and key socio-ecological systems is too fragmented for informed decision making. Furthermore, the responsibility for who addresses (and benefits from) the plastic problem is poorly understood and often disputed.

For example, who depends on plastic and why? Who are the winners and losers in relation to plastic? Where does the power to change lie? Is it really down to public behaviour and consumer choice or should the responsibility lie with those who produce plastics, dispose of it, or recycle it? Is it down to the companies that utilise and market plastic products, or should there be further governmental legislation to control which plastics are produced and utilised, and how they are disposed of?

There is an urgent need to radically shake up the way we approach the plastic problem; a social and environmental imperative to move from an imagined future with sustainable plastic, to a real one. By drawing on innovative cross-disciplinary research, we can create a joined-up approach and a comprehensive roadmap forward.

This requires an open, honest and inclusive societal conversation about the ways in which we currently produce, utilise and market plastic, and the realities and fictions of the move towards bioplastic and biodegradable plastic. It is only by tackling plastic in a systematic way – within its broader social and environmental context, examining its production, usage, reusage and end of life – that allows us to propose novel whole systems solutions, radical new ways of thinking or the development of new materials, in order to move towards this sustainable plastic future.

THE PLASTIC PROBLEM

Imagine if we had circular solutions for plastic that were perfect, carbon zero, regenerative, socially and environmentally responsible and economically viable.

Of course, this is not currently the case, and the avalanche of plastic has been gathering pace for decades. Since plastic became widely commercialised in the mid-20th century, the world has produced over 10 billion tonnes[1] and thrown away almost 8 billion tonnes.[2] Of the plastic in the UK, 37% has been sent for recycling, 44% incinerated for energy recovery, and 19% has gone to landfill.[3]

Plastic demand has almost doubled since the turn of the century[4] and causes damage estimated at $75 billion a year.[5]

More recently, the COVID-19 pandemic has added to the global avalanche of plastic. Billions of facemasks, gloves and lateral flow tests, millions of tonnes of home delivery food cartons and packaging for the online shopping boom all contributing to the problem[6], whilst policies limiting single-use plastic were rolled back. And it's going to get worse. Production capacity is expected to double by 2040[7] as oil companies seek to replace falling revenues from transport fuel as the sector decarbonises.[8] On current trends, plastic waste in landfill, or the natural environment, could double to 12 billion tonnes by 2050.[9]

Waste entering the ocean each year could triple from 10 million tonnes to almost 30 million tonnes by mid-century.[7]

The Changing Raw Materials of Plastic

The materials for most plastic today are supplied as a by-product of producing refined fuels from crude oil and natural gas As the world transitions away from using fossil fuels for energy, where will the raw materials for plastic come from in the future? The raw materials of plastic have changed before in response to wider shifts in industrial and energy systems.

The production of plastic has historically relied on the cheap by-products of other industries for its feedstock. For instance, the cellulose nitrate used to make 19th century plastic, such as Parkesine and Celluloid, came in large part from cotton mill waste. As Alexander Parkes noted in 1865: 'One of the means which enable [me] to produce Parkesine at a cheap rate, is the employment of waste cotton, in the shape of rags or otherwise, which are procurable at an exceedingly low price.'[10] The next generation of plastics, notably Bakelite, were also conjured from industrial waste products, this time coal tar. A by-product of processing coal into coal gas or coke, coal tar could be refined into phenol, one of Bakelite's principal ingredients. Post-WWII, plastic production realigned itself to take advantage of a new source of raw materials, as the oil industry's grand expansion created a plentiful supply of petrochemical by-products, meaning plastic could be produced cheaply.

Plastic is everywhere, and gets everywhere, because it is fantastically useful and cheap. It is strong, light, easily moulded, waterproof and flexible or rigid according to purpose. These properties have driven plastic from almost nowhere in the first half of the 20th century to ubiquity today, in products as varied as auto and aerospace components, domestic appliances, computers and mobile phones, footwear and clothing, water pipes and construction, medical equipment, shampoo and cosmetics, and – 40.5% of the EU total – packaging, including both commercial and industrial uses.[11]

Today the plastic industry produces 348 million tonnes and earns over $522.6 billion per year.[7]

Very often, plastic products have been seen to perform better than those they replace. Plastic technologies have repeatedly been central to new innovative products, which would have been unimaginable using previously existing materials; it is difficult to imagine a wooden laptop. Plastic is often claimed to benefit the climate, since it is lighter than the alternatives and transporting it consumes less fuel, or it reduces food wastage from which emissions would be worse. Yet making and disposing of plastic also emits lots of greenhouse gases at a time when we need to get to net zero. The chemicals sector emits around 1.5 Gt CO_2 per year, 18% of industrial CO_2 emissions, and is the second largest industrial emitter of NOx and SO_2.[4]

Moulding Markets – The Bakelite Age

Plastic is the natural choice for making all manner of things today, but there is nothing natural about how plastic became so ubiquitous in the first place, as the history of Bakelite shows. Patented in 1909, Bakelite was the first synthetic plastic and its widespread use in millions of everyday items came to define a whole era of the history of plastic. Yet the creators of Bakelite faced not just the scientific challenge of making a radically new material, but also the business challenge of getting manufacturers and consumers to buy an unfamiliar and unproven substance.

In the decade after its invention, the uses for Bakelite were limited to electrical components and insulators, but in the 1920s the Bakelite Corporation started targeting the mass consumer market with a twofold strategy that built supply and demand. On one hand, the Bakelite Corporation launched advertising campaigns to promote Bakelite as 'the material of a thousand uses' and created a popular image of a wondrous and desirable new material. On the other hand, the company worked with manufacturers and designers to help them create products that would realise this dream. Bakelite hosted design seminars to entice prominent designers into using the material in their creations. As well as promoting Bakelite to industry, Bakelite salesmen were also engineers who helped manufacturers make the transition to using it in their products, assisting with designing custom moulds or solving technical problems.

Bakelite adverts claimed it replaced traditional metal and wood 'entirely on merit.' However, the reality was that its success was facilitated by the Bakelite Corporation building relationships with designers, manufacturers and consumers, an example that those considering the next generation of plastic substitutes may learn from.

Plastic pollution is not just unsightly, but also causes environmental damage that we are only beginning to understand. Pictures of marine mammals entangled in plastic are distressing but only the most visible aspect. Over time, plastic breaks down into smaller and smaller pieces, and the smallest may cause the most damage. To date, we have only scratched the surface in our understanding of the scale of the potential impacts and dangers of plastic particles within our environment. We do know that plastic particles and additives get into the food chain and some can harm the human endocrine and immune systems, or even cause cancer. According to one assessment, 'plastic nanomaterials released into the environment could be the asbestos of the seas.'[12]

Even more plastic waste ends up in the soil. Here, the endocrine disrupting particles and additives not only enter the human food chain but can also interfere with the reproduction of soil micro-organisms that are vital for the growth of plants and crops. Some scientists fear this could lead to a collapse in soil fertility.[13,14]

The good news is that 200 countries have agreed at the UN to negotiate a legally binding treaty to regulate the industry so that future generations 'may live with plastic and not be doomed by it'.[15]

The big question remains: what should they agree? At a minimum, the treaty must be compatible with the UN's Sustainable Development Goals (SDG).

Table 1 outlines just some of the positive and negative relationships between the SDGs and plastic. It is hard to see how the SDGs can be achieved without developing systematic solutions, such as a circular plastic economy, which seeks to eliminate emissions of greenhouse gases (GHG) and local air pollution, while optimising the positive impacts of the scarce resources used to make plastic.

UNITED NATIONS SUSTAINABLE DEVELOPMENT GOALS	PLASTIC
End hunger, achieve food security and improved nutrition and promote sustainable agriculture.	Plastic packaging extends the life of food, increases its transportation and reduces levels of spoilage, allowing more of the food grown to be usefully consumed. Plastic can be used in agriculture to improve crop yields, reduce weed infestation and extend the growing period.
Ensure healthy lives and promote wellbeing for all at all ages.	Plastic plays a critical role in providing sterile instruments, dressings and medication. Plastic protective equipment is essential for avoiding cross contamination and disease transmission. Ingestion of plastic can create health problems.
Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.	Plastic products are extensively used in schools and other learning environments. These include laptops, pens, teaching aids, folders, desks, chairs.
Achieve gender equality and empower all women and girls.	Plastic plays an important role in sanitary and period products and preventing the negative social impact of period poverty. Many plastic products improve the efficiency of many tasks such as fetching water an washing, tasks which fall disproportionately on woman and girls. This can extend the accessibility of education to women and girls.
Ensure availability and sustainable management of water and sanitation for all.	Plastic is used for pipes and other water and sewage treatment infrastructure. Plastic can be used to store and transport clean potable water, as well as safely disposing of sewage.
Ensure access to affordable, reliable, sustainable and modern energy for all.	Plastic is an essential component of most renewable energy solutions and energy transmission systems.
Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.	Plastic is a key component of many product value chains, including products considered to be sustainable. Plastic products play an important role in protective equipment and health and safety systems in workplaces.
Build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation.	Plastic is critical to almost all infrastructure and construction projects. Plastic is almost integral to the extension of digital services and innovation.
Make cities and human settlements inclusive, safe, resilient and sustainable.	Plastic plays an important role in improving food security, personal mobility, disease control, access to clean water, and other prerequisites of sustainable communities.
Ensure sustainable consumption and production patterns.	Plastic can play a positive role in the responsible production and consumption of products. However, if used inappropriately, excessive use of plastic can result in unsustainable impacts.
Take urgent action to combat climate change and its impacts.	All plastic (and the materials it could replace) has a carbon footprint, which must be taken into account in their production, use and disposal.
Conserve and sustainably use the oceans, seas and marine resources for sustainable development.	Plastic waste is a major pollutant in marine environments, something which needs to remediated and actions taken to prevent future problems.
Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification halting and reversing land degradation, biodiversity loss.	Plastic waste is a major pollutant in terrestrial environments, impacting on soil fertility, biodiversity and individual species. These problems need to remediated and actions taken to prevent future problems.

Table 1: Examples of relationships with plastic and the SDGs[16]

Questions remain as to whether this welcome UN initiative will be enough. Given the known risks to human, animal and environmental health, and the gaps in our knowledge, plastic pollution could prove as existential a threat to humanity as climate change. To combat this, it is not enough to simply manage plastic; we must fundamentally reimagine it. The problem the UN hopes to solve over the next two years is wickedly complicated and there remain many significant gaps in our knowledge. To find the answers, we first need to work out the questions.

The big picture

With all the publicity around plastic pollution, it is easy to forget how many benefits plastic has produced. It is hard to imagine an effective response to COVID-19, for example, without billions of pieces of PPE and testing kits. Plastic has long protected lives in medicine, and in infrastructure: plastic pipes eliminate the risk of contaminated drinking water posed by lead ones. More generally, plastic has made products lighter, often more durable, and cheaper than they would otherwise be. It is also surprising to realise that some plastic products were originally conceived to protect nature; Bakelite billiard balls replaced those made of ivory; plastic bags were invented to save trees.

Despite all the benefits, however, the focus is now rightly on the damage done through carbon emissions and environmental pollution.

The material of a thousand uses?

It is easy to conceive how plastic could be replaced in any particular application, but the sheer number of different uses of plastic makes the task seem enormous. How can one replace such a versatile substance? However, plastic's ubiquity does not entirely rest on its physical properties, but also on a long history of plastic being promoted as somehow uniquely versatile, even when this was not entirely true. Understanding of traditional materials, like metal and wood, was established over centuries. However, those promoting early plastic had to establish what plastic was in the public mind, how it behaved and what made it special.

To do so, they stressed its versatility, highlighted its physical properties and showcased its many uses. In 1865 Alexander Parkes explained that Parkesine could be used for everything from 'knife handles, combs, brush-backs, shoe soles, floor cloth, whips' to 'works of art [and] insulating telegraph wires.' By the 1890s celluloid salesmen were lugging around cases full of 'a really extraordinary… number of articles from celluloid collars to ivory-backed mirrors,' to win people over to their new material. Decades later, Bakelite's adverts declared it the material of a thousand uses and highlighted its physical attributes: 'special insulation properties, it's toughness and the ease with which it can be machined,' or 'strong yet, wondrously light.'[10] However, early plastics were sometimes ill-suited for their applications.

Parkesine products tended to warp and shrink. Celluloid trinkets had an alarming reputation for bursting into flame and celluloid dentures softened when the wearer consumed a hot drink. Bakelite was inflexible, brittle and could only be made in a limited range of dull colours, acceptable in industrial components, but a drawback for many consumer goods. Nevertheless, the materials came into widespread use and sparked the development of new plastics better suited to the uses being found for them. In hindsight, plastic's versatility was partly a self-fulfilling prophecy, a promise made and fulfilled by the plastic industry. Once we understand this, it becomes easier to envisage how new materials could gradually become just as widespread as the traditional plastic they replace.

Environmental pollution

Unfortunately, the properties that confer many benefits to plastic are also those that mean it can persist in the environment for hundreds or thousands of years. Plastic waste never biodegrades into natural substances – at least not in a meaningful human timespan – but does break down into smaller and smaller particles. Even as invisible micro and nano-plastic particles they continue to do damage, perhaps even more so.

Some effects on human health have already been established. Production of petrochemicals causes high levels of local air pollution; the chemicals sector is the second largest industrial emitter of NOx (Nitrogen oxides), SO_2 (Sulfur dioxide) and a big emitter of VOCs (Volatile Organic Compounds).[4] One stretch of Louisiana, known as 'Cancer Alley', that hosts a high concentration of petrochemical plants has an age-adjusted cancer incidence per 100,000 population of 482.2 compared with a rate of 448.6 for the US.[17,18]

In many plastic products, additives such as bisphenol A (BPA) are known to harm the endocrine (hormone) and immune systems and can cause cancers and loss of fertility, shown in both humans and other animals.[19] BPA is short-lived, but its prevalence makes it an important pollutant. BPA has been banned in many food sector consumer products, such as baby bottles in the US, Canada and the EU.[20]

Microplastics (smaller than 5mm) have been found in human faeces and even blood.[21] The World Health Organisation (WHO) has found that there is not yet conclusive evidence that microplastics in drinking water cause harm, but stresses that the problem has not been studied well enough.[22]

For instance, an American study has found some evidence to suggest that an adult male ingests and inhales over 110,000 microplastics per year,[23] although research into microplastic inhalation and its effects is still only just beginning.

In the natural course of things, most microplastic that people ingest will end up, in higher-income countries at least, at a wastewater treatment plant. These are rather efficient at capturing microplastic from effluent and typically catch 83%.[24]

The sewage sludge is often then spread on arable land to improve soil fertility. But since the sludge is packed with microplastic, it may be having the opposite effect. And if microplastics find their way into ground water reserves, it could lead to severe and long-lasting (centuries to millennia) environmental impacts and costs for the water industry.

Agriculture uses 12.5 million tonnes of plastic worldwide each year – for mulching, polytunnels, packaging and the encapsulation of seeds and agro-chemicals such as fertilizers and pesticides – most of which is not collected.[25] In lower-middle income countries, up to one third of all cows and half of the goats have eaten plastic, which reduces their growth and milk production, and eventually kills them.[26]

Although plastic helps save lives in many circumstances, plastic pollution can also potentially kill. Research by Tearfund found that between 400,000 and 1 million people die each year in lower-middle income countries because of diseases related to mismanaged waste – as many as two people a minute.[26] Waterways blocked by plastic waste, for example, create breeding grounds for disease-carrying flies, mosquitos and vermin, and double the incidence of diarrhoea, the second leading killer of children under five. Open burning of plastic releases air pollution that increases the risk of respiratory and heart disease as well as cancer and could cause up to a fifth of the 3.7 million annual deaths from outdoor pollution.[26]

The oceans currently absorb 10 million tonnes of plastic waste each year – forecast to triple to almost 30 million tonnes by 2040.[7] Programmes such as *Blue Planet* highlighted the plight of whales and turtles that starve or choke after eating plastic or becoming entangled.

Although distressing, the impact of plastic on marine mammals is simply just the most visible part of the problem. Research shows that, of 550 species of fish studied, two thirds had ingested plastic. This included 210 species that are commercially important, and predators such as tuna were more likely to have eaten plastic – so concentrating plastic into the human food chain. The researchers weren't always able to look for microplastic but, when they did, they typically found that the more they looked for smaller particles, the more they found.[27]

More broadly, the damage to fisheries world-wide has been estimated at $13 billion a year, and to the environment as a whole at $75 billion a year.[5]

Emissions

It is often claimed that plastic reduces carbon emissions because, for example, plastic bottles are lighter than glass ones, and therefore take less fuel to transport, or because airtight packaging reduces food waste, which on balance would have caused larger emissions.

The logic sounds plausible and, on its own terms, may often be right. But there are two problems with this general view.

Firstly, these claims are based on lifecycle analysis (LCA), which suffers many widely accepted weaknesses. The analysis depends critically on choices and assumptions made by the analyst, particularly where the boundaries are drawn. Sometimes the plastic benefits from a hidden carbon subsidy because it is considered a by-product of fuel production. Often the analysis focuses only on carbon and ignores wider environmental problems of plastic 'afterlife'. Very often, LCA is funded by companies with a commercial interest in the outcome. Secondly, regardless of the claimed benefits of any individual plastic product, the overall carbon emissions from plastic production and disposal are high. The chemicals sector emits around 1.5 Gt CO_2 per year, 18% of industrial CO_2 emissions.[4]

In Britain, since the phase-out of coal-fired power, energy from waste (EfW) is now the most carbon intensive form of electricity generation, more than twice the grid average – because it burns so much plastic.[28]

These emissions must still be eliminated if we are to reach net zero – regardless of the counter-factual.

How and why does plastic get into the environment?

As litter-strewn as our streets may sometimes seem, in rich countries, rubbish collection systems are generally efficient. In the UK, for example, most plastic is captured and 37% sent for recycling, 44% incinerated for energy recovery, and 19% sent to landfill.[3] See Figure 2 (Page 17) for a further breakdown of plastic end of life data in the UK.

Aside from illegal fly-tipping, of which there were 1.13 million cases in the UK last year,[29] not much gets past the formal collection system (huge volumes of microplastic still escape into the environment, however, through wear and tear of car tyres, textiles etc).

In lower-middle income countries the picture is rather different. Two billion people worldwide – a quarter of the world's population – have no access to rubbish collection. For another 1 billion, waste may be collected but then discarded unsafely. In the poorest countries, over 90% of waste is burned in the open or discarded on roads, land or rivers.[26]

Lightweight plastic waste simply blows out to sea or floats downriver. As a result, it's estimated that while about 80% of the plastic waste in the ocean originated on land, the rest has either never been collected, or has escaped from poorly managed waste systems.[30,31]

The latest research suggests that more than 80% of plastic waste in the ocean comes from countries in Asia – and not necessarily the largest. The Philippines alone accounts for over a third because there are large coastal populations living on many small islands with high rainfall and inadequate waste management systems. India generates 13%, China 7%, and Europe and Oceania cause less than 1%. Even on a per capita basis, Europe emits 0.1kg of plastic waste to the sea while the Philippines emits 3.5kg/person.[31] However, it is worth noting that at least a portion of this waste has originally derived from higher-income countries which export their plastic waste for disposal elsewhere.[32]

If there were agreed global standards and support for better collection and management of plastic waste to the same standard as rich countries, it would mean a massive reduction in ocean pollution. This would need to recognise that plastic waste in one region can be intrinsically linked in a number of ways to plastic production or usage in another. Unfortunately, better waste collection and management is not the end of the problem.

Landfill causes 11% of global methane emissions, and EfW emits large amounts of CO_2, particularly where, as in Britain, EfW waste heat is not generally exploited.[33] In any case, neither approach is circular or sustainable. And none of this solves the carbon emissions of producing plastic.

Nor is litter the only way that plastic escapes into the environment. Macro-plastic such as bottles and bags break down into secondary microplastic (less than 5mm) and eventually nanoplastic under the effect of UV and mechanical forces such as wave action. There are also primary microplastics that escape into the environment, such as micro fibres washed out of clothing. Microbeads in cosmetics have now been banned in the EU and UK, but microfibres are still a problem.

Filters are available to install in washing machine wastepipes and alongside postal recycling services, but the recycling cartridges and shipping are relatively expensive.[34]

What about recycling?

In the UK, there is broad public enthusiasm for more efficient forms of recycling. In our survey of British public attitudes, 87% agreed that as a society 'we should be looking into better ways to recycle'.[35] Like waste collection and management, it is plainly better to recycle than not: it generally conserves energy, emissions and resources. But again, that is far from the end of the problem.

First, recycling hardly ever happens. Of the almost 8 billion tonnes of plastic waste discarded to date, only 9% has been recycled. Even today, only 20% of plastics worldwide is recycled compared to 80% for steel.[4] But even if all plastic was recycled, there are significant drawbacks with existing technologies.

The most common form is mechanical recycling, in which plastic is sorted into various types, polyethylene terephthalate (PET), high-density polyethylene (HDPE) etc. This is then washed, shredded, melted and re-extruded into pellets to manufacture new products. This generally consumes less energy and emits less CO_2 than producing virgin plastic.

Whilst mechanical recycling is generally considered to be the most cost-effective method of recycling plastic, the problem is that separation of different plastic streams is never perfect, and because each stream is always likely to be contaminated with other types of plastic, food residues or dirt, the chemical properties of recycled pellets will be inferior to those of the virgin material. This causes 'downcycling', in which food grade plastic is recycled into (say) car components and those into (say) garden furniture. Typically, virgin plastic will go through only three cycles before ending up in landfill or EfW. So mechanical recycling only defers final disposal, and carbon or methane is still emitted.

Chemical recycling goes one stage further. Techniques such as pyrolysis and gasification recycle plastic by heating them to high temperatures in conditions of low or no oxygen, which degrades the plastic without combustion, producing an oil or gas that can be used to produce virgin-quality plastic.

Many different types of plastic can be processed simultaneously – including soft plastic, which can't be recycled mechanically – which reduces the need for sorting. PVC can be recycled chemically once separated. All this goes some way towards solving downcycling. But chemical recycling is typically energy intensive and might consume a fifth of the energy contained in the plastic – although the necessary heat could be provided by an external source of renewable energy.

There are, however, some encouraging developments in this area. Several companies have invented new technologies to recycle polyethylene terephthalate which is commonly used to make drink bottles, carpets and clothing using milder depolymerisation technologies generally known as chemical recycling to monomer (CRM). These technologies can even recycle coloured PET into new food-grade PET by breaking the polymer chains back down to monomers that can be purified and repolymerised to give PET that is chemically the same as the virgin plastic.

Alternatively, biological recycling captures several different technologies that use biological processes to depolymerise plastic. On one hand, enzymatic processes that are comparable to some chemical depolymerisation methods are being investigated, and have potential advantages of operating at lower temperatures than current chemical solutions — potentially with higher selectivity. Currently these technologies are generally slow and can be limited by highly crystalline feedstock materials.

These biological and chemical methods claim to make PET recycling entirely circular, which is encouraging – although PET represents less than 10% of all plastics.[9]

Other biological recycling methods include industrial composting or anaerobic digestion. These methods are highly specific and can only be applied to a very limited set of plastics. While they are a promising way to deal with plastic waste, questions remain about what remains of the plastic and what impact these have once the composted matter is introduced into the soil biome.

So, existing recycling technologies either fail to conserve molecules and avoid greenhouse gas (GHG) emissions for long or are energy intensive and therefore expensive.

SURVEY BOX: WHAT DO THE PUBLIC THINK OF RECYCLING?

In the UK, public attitudes towards recycling of plastic suggest that we are failing to deliver on public expectations of what good recycling might look like. The results of our survey suggest there is a desire for recycling to be more efficient, easier to understand or simpler to undertake; most importantly for the recycling of our plastic to be globally, socially and environmentally responsible.

Almost 9 in 10 people (87%) think that as a society we should be looking into better ways to recycle.

Just over 8 in 10 people (82%) think recycling should be completed in the UK, and we shouldn't send our waste abroad.

Almost 3 in 4 people (74%) admit that it is hard to understand exactly what plastic can or can't be put in recycling bins.


Reciclável

Why not replace fossil feedstocks with biomass?

In principle, any plastic currently made from oil or gas could also be made from plant material. After all, fossil fuels are only plant and animal remains that have been pressure cooked by geology for millions of years.

So, should we be replacing fossil-based feedstocks with those that are based on biomass?

The answer is unclear — and reflected in the confusion around the term 'bioplastic'. Many people assume this must mean the plastic is both sourced from biomass and, if it escapes into the environment, will naturally 'biodegrade' (although that term, too, can be misleading). But the origins and behaviours of plastic are separate issues, with different implications for carbon emissions and environmental pollution. See Figure 1 for a further breakdown of the term bioplastic.

A plastic made from corn sugars, for example, might well have a smaller carbon footprint than one made from oil or gas (depending on the full lifecycle). But if it needs to perform in the same way as the fossil plastic, the sugar will be turned into the identical polymer, which will no more degrade in the environment than the fossil version. So a product made of BioPE could just as easily end up killing a turtle as one made of fossil PE and would eventually break up into microplastic. Despite its 'bio' origins it would cause just as much trouble.

Other bioplastic, like the gossamer-thin 'compostable' bags many publishers now use to post magazines to their subscribers, can be made to degrade quickly under certain conditions. But some may need the higher temperature of an industrial composter, and bags that escape into the environment may still persist for a long time as litter.

But if bio-sourced plastic can be both lower carbon and compostable or digestible, wouldn't that be better? Again, the answer is not yet clear.

Whether or not the bio-sourced plastic has a lower carbon footprint depends on the full lifecycle. If the plastic were ever to end up being burned in an EfW plant, then the bio-sourced plastic could be considered climate neutral, whereas the fossil plastic would increase CO_2 emissions.

However, we also need to acknowledge that moving away from fossil fuel feedstocks may also have unintended social, environmental or geo-political impacts or implications.

The mouldable definitions of 'plastic'.

The meaning of the word 'plastic' is as mouldable as the materials themselves and has shifted several times over history. In the 19th century 'plastic' was commonly an adjective, not a noun. When early synthetic materials, like Parkesine and Celluloid, were described as being plastic, people meant they had the physical property of being easy to mould, not that they were examples of a category of material called plastic.

At first, early synthetic materials that we now think of as being plastic were commonly known under their own distinct brand names, most famously Bakelite, rather than under the banner of 'plastic'. This was straightforward enough when there were only a few such materials available, but in the 1920s and 1930s many new synthetic materials were created. To save confusion, people started to refer to them collectively as plastic, a term which came to refer to a whole new category of materials. As one newspaper remarked in 1933: 'Many other resins are made from exactly the same materials as Bakelite, and are marketed under different trade names. "Plastic" is their general name, just as piano is the general name for a special kind of musical instrument.'[36]

In recent years the meaning of plastic has started to shift again, albeit by implication. With manufacturers now offering many products described as 'zero-plastic' or 'bioplastic', plastic increasingly means a synthetic material made from fossil fuels. The irony is that the bioplastic used in many 'zero-plastic' products is plastic, just one made from a renewable biomass material, such as wood pulp, rather than a fossil fuel.

What does biodegradable mean?

If something 'biodegrades', it decomposes through natural biological processes. Worms and micro-organisms will soon reduce vegetable peelings to fertile compost, for example. But in marketing-speak, 'biodegradable' is an umbrella term that covers various processes and can cause confusion.

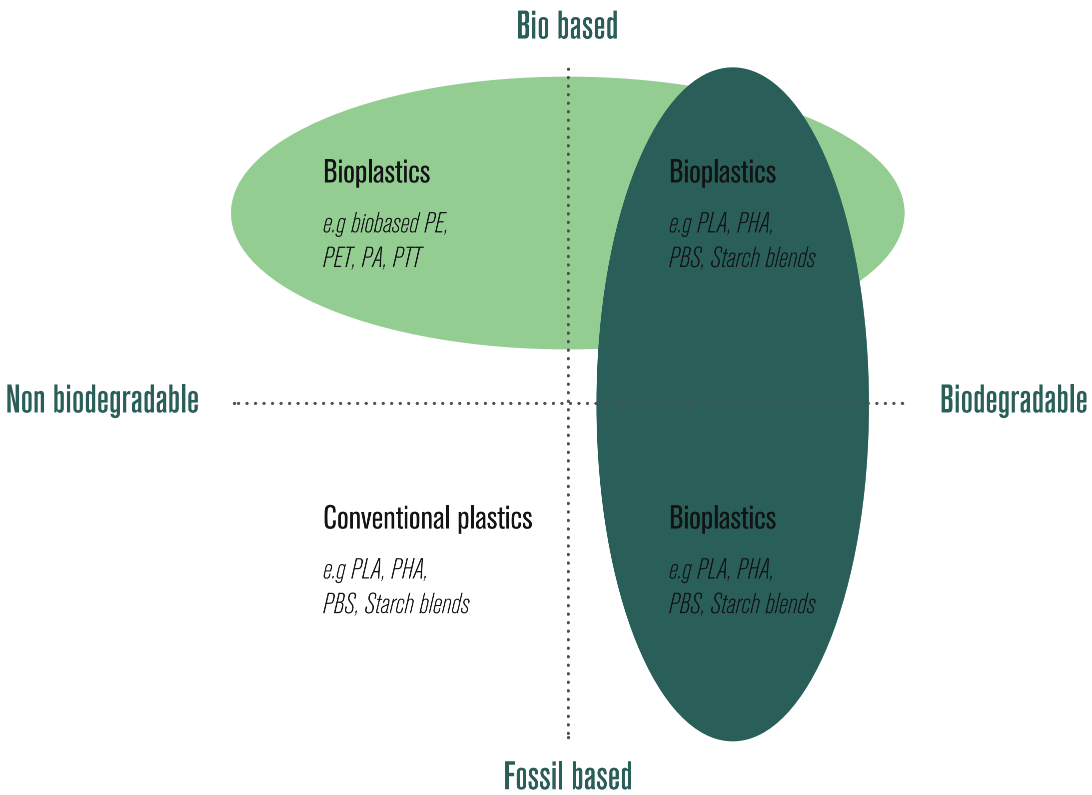
A plastic that is 'compostable' is, by definition, biodegradable but may only biodegrade in specific circumstances. The majority of plastic marketed as compostable may only break down in an industrial composter that reaches around 50-60°C. Throw it into your home compost and it will remain intact for years.

Another form of biodegradation is anaerobic digestion (AD). AD plants mimic the processes inside the gut of a cow to break down organic matter. And some plastic bags labelled as biodegradable are designed to be digestible. These will never degrade in the open air, only if passed through an AD plant — or a cow. Likewise, if you put a compostable bag through an AD plant it will emerge unscathed.

The ways in which biodegradable or compostable plastic are marketed, sold and promoted are often misleading. Our survey suggests that the public's expectations of what types of plastic or processes should be labelled as biodegradable does not match the reality of the way in which the term is being utilised by commercial interests.

- When asked what percentage of plastic labelled 'compostable' could be composted at home, or had to be composted under specific conditions using industrial equipment, **almost 3 in 5 people (59%)** said they did not know.
- **1 in 5 people (20%)** think biodegradable plastic can be thrown into landfill and will break down doing no environmental harm.
- **Almost 1 in 4 people (24%)** think biodegradable plastic always break down within at least a few years in the environment, while **around 1 in 12 (8%)** think they always break down in a matter of months.
- **Just over 1 in 2 people (52%)** think plastic labelled 'biodegradable' should take less than a year to break down.

FIGURE 1: DEFINING BIOPLASTIC



Source: European Bioplastic[37]

SURVEY BOX: WHAT DO THE PUBLIC THINK ABOUT BIOPLASTIC?

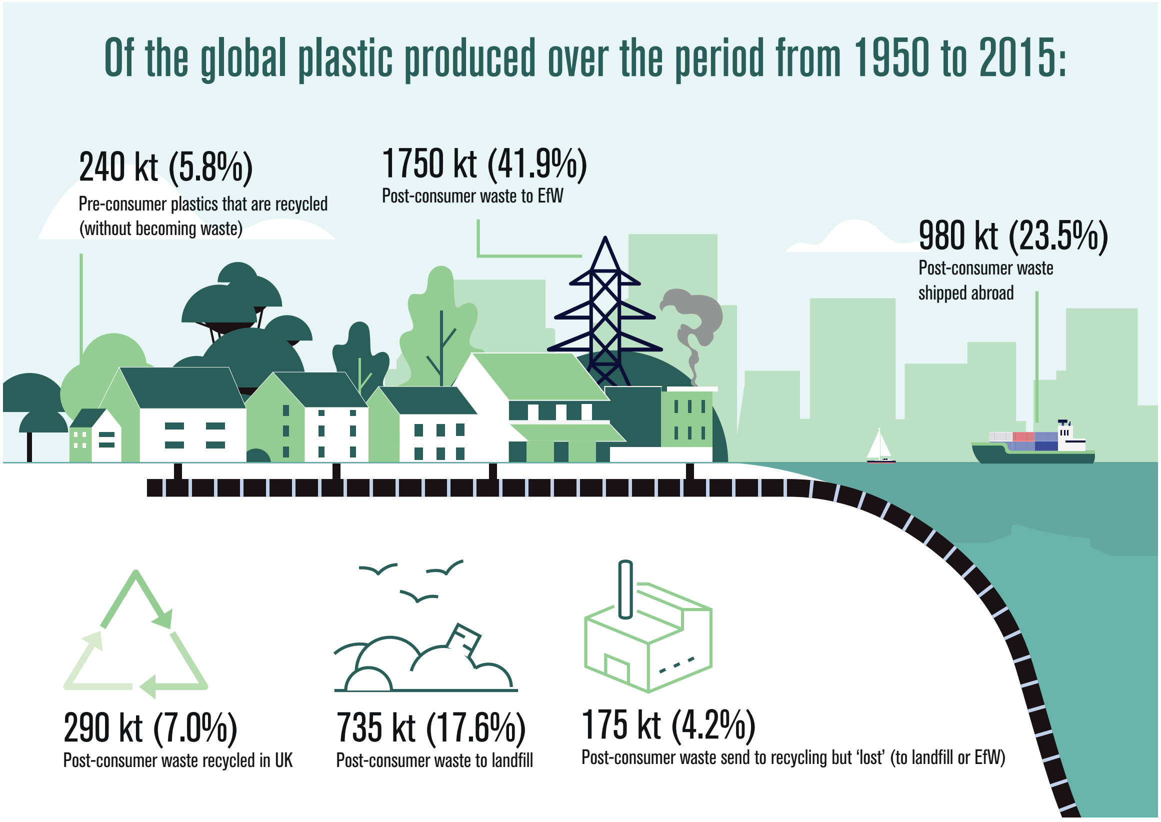
Similarly to the term 'biodegradable', there is a mismatch in the public expectations of what the term 'bioplastic' should be applied to and the reality of the ways in which the term is used and promoted. This suggests that the term 'bioplastic' has a greenwashing effect – in that it implies they are intrinsically less damaging to the environment than fossil fuel derived plastic when this is not always the case.

Around 1 in 7 people (15%) believe bioplastics are all biodegradable, and the same amount of people think bioplastics always break down into biological matter.

Just over 1 in 3 people (35%) think bioplastics are always easier to break down than fossil fuel derived plastic.

Only half of people (50%) correctly noted that bioplastics can still contribute to plastic pollution.

FIGURE 2: PLASTICS PRODUCED – UK



Source: Plastics Europe[3]

There remains, however, the question of natural resources.

Some scientists argue that the amount of land necessary to replace fossil feedstocks in plastic production is impossibly large, while some bioplastic producers argue that, in the context of existing agricultural and fallow land, the figure will be trivially small. Debates that posit fossil versus bio feedstocks can only get us so far. We need to examine systemic solutions that take into account the full picture of climate change, habitat destructions and biodiversity loss alongside human health and wellbeing.

Simply changing from one feedstock to another may simply overlook, or mask, the wider environmental and social impacts of current plastic production and usage. Wherever the balance lies, it remains true that deforestation continues to set new records, even under current population and demand pressures – never mind adding a whole new category of demand.

If fossil fuels were kept as plastic feedstock and transport were decarbonised, as we hope, it would raise other questions about the extent to which refiners could convert the (large) fractions of each barrel, previously used for transporting fuel to petrochemical feedstocks.

On the other hand, if we accept that a perfect waste system that prevents any plastic escaping into the environment is unlikely, then designing plastic to biodegrade benignly – degrading into sugars or perhaps even fertilisers – becomes essential.

Finally, there are many plastics that must not biodegrade under any circumstances while in use in the environment, such as water pipes, aerospace components, and perhaps most critically – medical implants. For these we will always need some form of mechanical or chemical recycling, or possibly EfW with carbon capture and storage (CCS).

Behaviour and business

Some people are litter bugs. Some can't be bothered to sort their rubbish from their recycling. Others do care but make mistakes – even in eco-friendly Sweden where households must separate their waste into eight different fractions. In our survey of UK adults, 74% admitted it was 'hard to understand exactly what plastic can or can't be put in recycling bins.' In the throes of a cost of living crisis, many people have more immediate problems to worry about and cannot afford products that may be less damaging but more expensive. Some experts even fear that labelling products or packaging 'biodegradable' creates a moral hazard: even more littering.

It seems no solution to the problem of plastic should rely wholly, or even largely, on voluntary consumer behaviour. Consumers, after all, can only respond to the choices they are offered and are often making decisions with incomplete or limited information, which is further compounded by misleading marketing or labelling of plastic products (such as 'biodegradable' or 'bioplastic'). Even well-meaning efforts can backfire; donating used clothes to charity shops in Britain leads to mountains of unwanted 'fast fashion' being burned in Ghana, for example, or fouling its beaches.[38]

At the same time, business models of multinational oil companies, consumer goods producers, and supermarkets are built on churning out single use plastic bottles, bags, and packaging.

Each sector wants to off-load responsibility onto the others. Oil companies want to frame the problem as one of waste disposal only, not the entire lifecycle, and lobbied – although unsuccessfully – for the UN treaty to take that approach.[39] (The industry will invest $400 billion over the next five years building 176 new petrochemical plants.[40,41]) Consumer goods companies want the issue to be solved by the plastic producers. The supermarkets' use of language in advertising plays down the stores' own role, placing undue responsibility on the customer.[42]

Different types of plastic packaging make up the largest single share of plastic usage. For example, in 2021 in the EU, packaging including commercial and industrial packaging, made up 40.5% of end use markets.[11] Whilst there are lots of products which simply do not need plastic packaging, many other products may still need to be packaged in plastic but could convert to a 'return and refill' business model. However, such initiatives may be limited in scope as they do not always consider the realities of many people's day-to-day lives. Convenience is not always a luxury, but in some cases a necessity for those struggling to meet the cost of living or the demands of dependent care and work. Furthermore, these kinds of approaches have been impacted by the COVID-19 pandemic, which possibly reflects consumers' concerns over food safety and hygiene. But at the very least, redesigning products and business models could shrink the size of the problem. In most of the world there is little incentive; the $75 billion 'externality' of plastic damage[5] to the natural environment is not priced in. Aside from the EU and UK, global plastic waste is not widely taxed.[43]

More broadly, we need to think about where plastic is strictly necessary and where it is not. It is hard to see any alternative for water piping, much medical equipment, food safety and aerospace components, for example. However, UPVC windows have a shorter lifespan than timber windows and are hard to recycle – though the timber 'alternative' does need to be protected with paint. We need to find a way to distinguish between the products for which plastic is vital and those that use it simply because its cheap. We must then use this distinction to inform policy.

Pathways

In an ideal world, we could enjoy all the benefits of plastic with none of the damage. But as we have seen, the very same properties of plastic cause both its advantages and disadvantages. As table 2 makes clear, none of the existing or foreseeable plastic pathways meets the ideal. There is no single clearcut solution to the problem.

For example, the first two pathways in table 2 represent business-as-usual in rich and poor countries. Neither is remotely sustainable. In rich countries, plastic is responsible for large GHG emissions, and the full extent of damage to soil, marine and human health is only in doubt because the research has not yet been done. In poorer countries, the damage is immeasurably worse and could be massively reduced simply by bringing collection and disposal infrastructure up to rich country standards. Marine macro-plastic pollution would fall dramatically, but microplastic damage to soil and human health, and GHG emissions, would still be unsustainable.

The remaining sample pathways all broadly meet the environmental conditions but come with big caveats on technology readiness, energy, cost and sometimes resource constraints. None looks like a universal solution.

SURVEY BOX: WHAT DO THE PUBLIC WANT FOR THE FUTURE OF PLASTIC?

We asked the UK public where plastic-related research funding should be prioritised. **Developing new types of material to replace current plastic was seen as the top priority (selected by 43% of people), ahead of developing new biodegradable plastic (33%) or bioplastic (22%).** Developing new ways to reduce the amount of existing plastic in the environment was the second most selected priority (41%), with 28% of people prioritising creating new recycling systems.

When asked to imagine a future where plastic is worth more than gold, 50% of people said their use should be prioritised in medical applications. The next two most popular priorities were building and construction (20%), and electrical and electronics (19%). **Just 16% said we should prioritise food packaging.**

PATHWAY	PLASTIC SOURCE	BIODEGRADABLE	END OF LIFE	DURABILITY[a]	CO_2[b]	SOIL/MARINE[c]	HEALTH[d]	RESOURCE CONSTRAINT	ENERGY CONSUMPTION	COST	TECHNOLOGY READINESS
1	Fossil	✗	Mechanical recycling + EfW or landfill	Good	Bad	Middling or unknown	Middling or unknown	Middling or unknown	Good	Good	Good
2	Fossil	✗	Poor landfill, open burning	Good	Bad	Bad	Bad	Middling or unknown	Good	Good	Good
3	Fossil	✗	Chemical recycling	Good	Good	Good	Good	Middling or unknown	Middling or unknown	Middling or unknown	Middling or unknown
4	Fossil	✗	EfW + CCS	Good	Middling or unknown	Good	Good	Middling or unknown	Middling or unknown	Bad	Bad
5	Fossil	✗	Mechanical recycling then chemical recycling	Good	Good	Good	Good	Middling or unknown	Middling or unknown	Middling or unknown	Middling or unknown
6	Biomass	✗	Landfill	Good	Good	Middling or unknown	Middling or unknown	Middling or unknown	Good	Good	Good
7	Biomass	✓	Chemical recycling	Middling or unknown	Good	Good	Good	Middling or unknown	Middling or unknown	Middling or unknown	Middling or unknown
8	Biomass	✓	Industrial Composting/ Anaerobic Digestion	Middling or unknown	Good	Middling or unknown	Good	Middling or unknown	Good	Middling or unknown	Good
9	CCS + Renewable H_2	✓	Chemical recycling	Middling or unknown	Good	Good	Good	Good	Bad	Bad	Bad
10	Fossil	✗	Enzymatic recycling	Good	Good	Good	Good	Middling or unknown	Good	Middling or unknown	Bad

Table 2: Plastic Pathways from source to end of life, with indicative impacts.

Notes:

Pathways 1 and 2 represent the current, commonly used approaches in rich and poor countries, respectively.

Other pathways consider other options (of course, many more are possible).

a) Long term durability of the product;
b) Impact on carbon dioxide release;
c) Impact on soil/marine health;
d) Impact on human health

Key
Good
Middling or unknown
Bad
EfW = Energy from waste
CCS = Carbon capture and storage

But perhaps we don't need a single solution. Since plastic performs many different functions and has widely differing properties, it makes sense that end of life pathways should differ too. For example, it seems unlikely that a water pipe could ever be devised that both performs well for decades underground and then degrades naturally in the environment.

By contrast, single use drink bottles, despite being some of the easiest products to recycle, are also among the most likely to escape into the environment, so a backstop of natural biodegradability would be more important. Because of the massive volumes involved, the additional energy and financial cost of chemical recycling might be prohibitive, or at least unnecessary.

The overarching question is, which combination of pathways could meet the environmental and other conditions to make plastic compatible with the SDGs – and which policies are needed to make it happen? No one organisation or country can do this on their own. Any pathways or solutions need to be collective and systematic in approach, bringing together organisations with different priorities and purpose around the shared common purpose of creating and maintaining systems of sustainable plastic production, consumption and re-use.

Any sustainable solutions will need the support of governments, citizens, consumers, businesses, financial markets, and civil society. Solutions that don't include all key stakeholders at best create fragmented temporary solutions that pass the risks onto others or simply 'kick the can' down the proverbial road.

Governments in the global north – particularly the EU and the UK – have introduced a variety of policies to reduce the damage caused by plastic and new legislature are being explored.[44]

In Britain, these include bans on some single-use products, deposit return schemes, extended producer responsibility and a £200/tonne tax on packaging that contains less than 30% recycled material.[45] But even these policies seem piecemeal and underpowered compared to the $75 billion annual damage attributed to plastic worldwide.

CONCLUSION

The mountains of words already spilled over the plastic problem almost match the piles of waste accumulating in landfill, soil and sea. And yet the problem worsens by the year. There are still big and worrying gaps in our knowledge and a high risk of unintended consequences. No analysis has yet shown how we plausibly get to environmentally-neutral plastic by the time we intend to reach net zero. That work is urgent; the University of Birmingham will lead activity to lay the foundations of the future we need to build.

Questions requiring answers associated with the re-imagining of plastic include:

- What are the outcomes under different future scenarios or system configurations?
- How should we best evaluate and prioritise all critical stages of the plastic lifecycle from monomer source to end of life?
- How are different opinions and values represented to ensure that the process of determining the future of plastics is transparent, justifiable and accountable?
- What are the technological gaps and how can they be filled?
- How can the solution incorporate risks, uncertainties or system thresholds and reflect power, conflicts and governance structures?
- What policies are needed to make a sustainable future with plastics happen?

We need to ask the fundamental question, who gets to define what 'sustainable' is when it comes to plastic? The terms of the debate are currently being set by plastic producers, those marketing plastic goods or recyclers who have a vested interest in its outcome.

By bringing together different disciplines and stakeholders from across society we are seeking to redress this balance and create entirely new pathways towards a sustainable plastic future.

This bringing together will allow the mapping of different stakeholder's responsibilities and accountability for the present problem as well as their capacity to transform it. A sustainable solution to plastic requires a collaborative approach, involving multiple stakeholders and engagement from different disciplines and institutions across the plastic value chains.

Unless we adopt a systematic approach now, the solutions of today are likely to be the problems of tomorrow.

CALL TO ACTION QUESTIONS

This review highlights many questions, several of which are outlined below, that warrant further consideration or require new evidence and information to enlighten discussion. These can be summarised in sections that address the following areas:

Recycling and reuse

- How can higher-income countries do their bit to help improve the waste collection and management systems seen in lower-middle income countries?
- What are the most viable new recycling technologies, how long would they take to scale, and to what extent could they solve the problem?
- What role should industrial composting or anaerobic digestion play in treating and recycling waste plastic?
- What is the true energy balance of pyrolysis and gasification, once products are purified for application, compared to other pathways?
- Will it be possible to capture all plastic waste for recycling? How does the changing proportion of captured waste affect the environmental impact of the plastic waste that results? In turn, what impact does that have on choosing the feedstock for plastic?
- How can plastic be changed, or mechanical recycling be optimised, to increase the amount of plastic that can be recycled through mechanical methods? What role should mechanical recycling have in the future recycling hierarchy?
- How can our recycling systems be better adapted to suit the plastics which are currently in production and circulation?
- Should we adapt plastic products to suit our existing recycling processes, or instead adapt recycling processes to suit our current plastic products? For either option, how can we enable these adaptations?

Fossil vs bio feedstocks

- How do greenhouse gas emissions for the production of fossil plastics compare with those from bio-based alternatives?
- What biomass resources would allow a wholesale change from fossil to bio plastics without leading to other environmental damage i.e. deforestation?
- What impact or implications would a shift to biomass plastics have on recycling systems and are these feasible?
- Can fossil plastics be made environmentally degradable, or fully recyclable in a closed loop? If so, and they don't compete with food production, is there a case to stick with fossil feedstocks?
- If demand for transport fuel goes into long term decline, what are the implications for the refining business, and in turn, would this benefit or disadvantage conversion of oil into plastics? What would be the cost implications on that plastic production and would this change the 'value' of plastic?
- What are the leading bioplastics and how can they be accelerated towards market adoption?

Sustainable business practices, consumer behaviour and policy

- How can policy best drive multinational companies towards business models that help solve, instead of worsen, the problem?
- How effective are existing company and industry initiatives to improve the sustainability of plastic?
- What behavioural nudges or policies are needed to encourage consumers to play their part?
- What criteria should inform any analysis of which plastic products are essential and which are not?
- What policies are needed to raise plastic recycling to the same proportion as steel or higher?
- How can recycling processes be simplified and be made more accessible for the public?
- Are there any pathways from plastic source to end of life treatment that look like dead-ends and if so why?
- Are there any gaps in the known pathways and if so what research is needed to fill them?
- Which combination of pathways will actually deliver the SDGs?

Environmental impact of plastic waste

- How do we eliminate carbon emissions from plastics?
- How do we minimise the amount of plastic that escapes into the environment?
- How do we render the impact of any plastic that does escape benign?
- How much do we know about how plastics break down in the environment?
- What do we know about the impact of plastics (and their degradation products) on human health?
- How much do we know about the impact on soil fertility and where are the knowledge gaps?
- How can we deal more systematically with micro-fibres?

Sustainability analysis

- To what extent can we rely on lifecycle analysis (LCA)?
- What principles, standards and guidelines could we impose to make LCA transparent and reliable?
- How can LCA reconcile climate damages and benefits with non-climate damages – or is it impossible?
- Is there a simple way to more holistically consider all aspects of the impact of plastic on the environment?

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