Plastics Research and Innovation Fund Conference

Creative Circular Economy Approaches to Eliminate Plastic Waste

UK CIRCULAR PLASTICS NETWORK

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Executive Summary

The UK Research & Innovation (UKRI) Plastics Research and Innovation Fund (PRIF) programme January 2018 – June 2020 commissioned 8 UK Higher Education Institutions (HEi) to research creative circular economy solutions to eliminate plastic wastes. Each HEI adopted their own research programmes based on their research strengths, had its own consortia of industrial, policy and wider stakeholders and were encouraged to collaborate and share learning between research groups. A small sample of early stage findings, outcomes and solutions were presented at a 2-day digital conference in July 2020, supported by 16 summaries published in this edition.

The initiatives were connected by two overarching approaches. Firstly, better understanding and evidence of the current plastic waste challenge, primarily UK focussed, and secondly solutions to create more effective after-use plastic economy. Some of the key headlines from these approaches are outlined below.

Quantifying baseline plastic stocks and flows and their impacts is important for monitoring purposes, to identify, target and prioritise the largest, most damaging flows but also to identify economic opportunities and inform policy makers. Yan et al. [1.2] and Domenech et al. [1.1] presented results of baseline plastic stock-flow modelling and mapping at household, regional and national scale respectively. Both highlighted the numerous sources of plastic consumed by different sectors (e.g. medical, fishing, agriculture, textiles, transport). Their analyses also highlighted the difficulty and complexity of modelling plastics stocks and flows, much of it hidden in products other than packaging, and the high proportion of plastics that are landfilled, incinerated or are found in the environment (for example from ghost fishing, plastic wastes in soil, fibres and microplastics from textiles, cleaning products and cosmetics found in waste water). In the paper by Hopkinson et al. [5.3], attention is drawn to the limited and fragmented scientific knowledge base to assess health or eco-toxicological impacts of different plastics. Farrelly et al. [4.2] explored the extent to which consumers and industrial stakeholders perceive plastics to be a problem, as the first step in understanding acceptance of potential solutions. In a similar vein, Domenech at al. [2.2] reported on citizen opinions and behaviour towards compostable and biodegradable plastics, highlighting that without appropriate systems in place that biodegradable plastics may soon become part of the problem rather than solution.

The papers reporting on **solutions** focussed on the challenge of legacy plastics; often designed for single use or the design of future 'circular' plastics and systems. The solutions presented were diverse but can be categorized under four primary CE building blocks: circular design; business model innovation; reverse logistics and system enablers (covering, behaviour change policy and regulation and citizens).

Circular Design: The effective design for Circular economy has many considerations but two key principles are avoiding adding hazardous or toxic substance to products (a safer by design philosophy) and design to ensure maximum value and material quality in multiple product and material life cycles (e.g. design for disassembly, recycling etc.). Hopkinson et al. [5.3] highlighted innovative SME companies recovering and upcycling plastic waste to higher value products. Dempster et al. [2.1] presented findings on creating bio-based polymers from bio-waste streams and plastics of the future from novel biocatalytic approaches.

Business Models: A business model is the way in which a business creates, delivers and captures value. A CE business model is designed to maximise value to all stakeholders including the principle of rebuilding and regenerating natural capital. Recycling remains an important business model for many legacy plastic wastes, hence finding ways to improve collection and yield is a key component of future CE plastic systems. Bexis et al. [3.2] addressed technical challenges in recycling PET and Mulakkai et al. [3.1] presented techniques to improve the mechanical recycling of multi-layer packaging. Tedstone et al. [3.3] reported on chemical and catalytic solutions for separating and valorising unavoidable healthware plastics. Greenwood et al. [1.3], described the results of novel reusable packaging systems – highlighting reduced waste and environmental impact.

Reverse Logistics: Reverse logistics normally represents the high proportion of costs of setting up circular economy systems. Burgess et al. [5.1] proposed and explored single bin solution to optimise the costs of collection and improve the quantity and quality of plastic for subsequent recycling.

System Enablers: Various system enablers were included in many of the papers cited above Allison et al. [5.2], Michie et al. [5.4] and Burton et al. [4.3] provided in-depth analysis examined barriers and enablers influencing individual and group/community behaviours, motivation and capabilities towards plastic recycling, repair and re-use. Boons et al. [1.4] highlighted the multidimensional nature of plastic economies and the timescales (decades) over which our socio-technical management of plastics and their disposal have evolved. Hopkinson et al. highlighted the diversity of plastic consumption and the need for long term policy, investment and networks for change to address the scale of the system redesign challenge.

Each consortium has continued its work since the conference and there are many more investigations across all 8 research groups. The discussions during the two-day event highlighted that there is no single solution to the challenge of plastic waste and leakage into the environment and a shared understanding of the pervasiveness of plastic in society – much of it hidden and not part of policy or public discourse on 'plastics'.

Given the complexity, high levels of uncertainty and fragmented data there is a continuing need for strong scientific, economic and behavioural evidence to underpin future policy, technical, regulatory decision making, especially potential health or eco-toxicological impacts. Finally, each paper provides insight and analysis to specific elements of future CE plastic systems. The academic teams remained optimistic large-scale plastic economy transformations are not only necessary but are achievable. For this to become a reality however will require a common CE vision, the right policies, long term research innovation and collaboration across all stakeholders involved in the production, consumption and disposal of plastic - in other words all of us.

Professor Peter Hopkinson, Exeter University PRIF

Introduction from Engineering and Physical Sciences Research Council (EPSRC)

Plastics are an integral and important part of the UK and global economy, due to their unrivalled functional properties and low cost. However, plastics use has a number of negative features, which need to be addressed to create a more sustainable economy, including environmental impacts and Greenhouse gas emissions.

Opportunities exist to address these features by radically transforming the UK's existing linear manufacturing and consumption pattern to a more circular model that employs next generation plastics and packaging formats. This could include:

- Cleaner and more recyclable plastic alternatives
- Recycling and recovery processes
- Improving the functionality of designed products
- Understanding of plastics materials flows within the economy
- Understanding to inform legislation and incentivise behaviour change.

The intention of the £20 million Plastics Research and Innovation Fund (PRIF) being delivered by UKRI, is to create a coordinated, integrated and aligned community of stakeholders from across academia, industry and government to catalyse new ideas and rapid solutions across the research and innovation landscape that are conceived to deliver a positive environmental benefit compared with current systems in both the short and long-term. The overall goal is to support the delivery of the Government's target of achieving zero avoidable plastic waste by end of 2042, within the context of the UK's commitment to bring all greenhouse gas emissions to net zero by 2050.

The three streams of activities being delivered are:

- Leadership and knowledge exchange: a UK Circular Plastics Network
- Research: Plastics 'Creativity' funding
- Business led research and development: Plastics 'Innovation' funding

This PRIF Research Conference brought together the eight academic projects funded in 2018 through the 'UK Research and Innovation Call for Proposals: 'Creative Circular Economy Approaches to Eliminating Plastic Waste'. These eight projects address a small section of plastics uses and its impacts within the UK. However, the solutions they have been researching have the potential for significant impact, including contributing to system-level change within this vitally important industrial sector.

This conference itself, and the work highlighted in this report, demonstrates the exciting way in which researchers from many disciplines, and across universities have come together in new ways to address the challenge.

Dr Rachel Bishop - EPSRC

Foreword

It was clear from the first time the PRIF projects got together that they would be more than the sum of their parts. With eight projects funded across the country, covering a wide range of plastics research, there was lots of scope for collaboration and interaction. When we offered in the kick-off meeting to host a combined end of project conference, none of us could have predicted this year's events. Last autumn we were eagerly planning a discussion style conference with papers grouped into topics that would enable spirited discussion and interaction. We settled on papers submitted in advance then groups of 3-4 papers giving short (max 5 minute) presentations, followed by 60 - 90 minutes facilitated questions and discussion. We wanted to spark lively debate and develop a roadmap for the way forward post-PRIF.

Then Covid-19 hit and there was no way we were getting together in person. We thought about cancelling/postponing, but we knew there was appetite for the discussion, investigators had already started writing their papers and we wanted to provide a platform for the PRIF teams, their stakeholders and interested others to share in our results. When we first suggested an online conference, our project admin team looked worried. It was a step into the unknown with a very short timescale to pull it off. They managed it magnificently. We have learnt a lot and there are things we would have done differently with more time, including facilitating informal networking (it's hard to beat the chat over a cup of coffee you can get in person), but the main aim - to spark lively discussion - was a great success. The online format actually enabled greater participation as everyone had a chance to ask their questions. There was interaction and input from industry and academics. In fact, there were so many pertinent questions it made chairing a challenge. We were able to bring in other speakers to contribute data to the debate. This type of panel discussion event certainly worked well with an online format. The conference was free to attend, and, as part of the PRIF research programme, funded by UKRI via the EPSRC.

Following the conference, authors had the opportunity to edit their papers to take into account the discussion. This publication contains the final edited papers, followed by a synthesis discussion and steps forward. We hope you enjoy reading it, we certainly enjoyed chairing the conference and pulling this publication together.

We would like say a big thank you to: our PRIF administrator, Steffi Tille, and all her colleagues in the other PRIF grants for pulling this together; Deborah Beck and Jana Kalalova from the Grantham Centre for Sustainable Future in Sheffield who were involved throughout and on the day Claire Moran for tweets; Adam McSweeney for technical support; and Sally Beken, the UK Circular Plastics Network and the the KTN team who have been supportive throughout and published this compendium.

Happy reading!

Dr Rachael Rothman and Professor Tony Ryan
University of Sheffield PRIF project leads and Conference Chairs

Plastic Sustainability Challenges

David G Bucknall[a]

The use of man-made (synthetic) plastics began in the early 20th Century and were specifically developed as cheap alternatives to expensive and/or resource restricted materials. Many of the most common polymers used today were developed by the 1950s's, by which time they had become aggresively marketed as cheap and disposable materials. This attitude to plastics persists to the current day, and is arguably the origin of the predominant linear economy of their use. However, these attitutdes have ultimately led to the current environmental crisis associated with mismanaged plastics. To prevent further environmental impacts by moving to a position of sustainability requires many challenges to be overcome. These challenges can broadly be grouped together as technical, societal, legal, political and economic factors. This papers provides a brief overview of some of those factors and potential solutions to achieving plastics sustainability in the context of their historic use.

Historical Perspective

The use of natural polymers has a very long history that dates back many millennia, but really developed commercially more recently. An early example is the discovery of vulcanized rubber by Charles Goodyear in 1839. Other modified natural plastics followed including linoleum introduced in the 1850s, celluloid in 1870, rayon in the 1890s and cellophane in 1912. However, the plastic that changed everything and started the modern man-made (synthetic) plastic industry was Bakelite. This plastic was developed by Leo Baekeland and his assistant Nathaniel Thurlow who were hoping to find a cheap alternative to shellac, which was made from the resin secreted by the East Asian lac bug. Bakelite was the first plastic synthesized entirely from small molecules, not by chemical modification of natural polymers. On discovering the synthetic route to Bakelite in 1907, Baekeland stated in his logbook "unless I am very much mistaken, this invention will prove important in the future". The introduction and subsequent massive exploitation of Bakelite is all the more remarkable given it wasn't until the seminal work of Herman Staudinger [1] and later confirmed by Wallace Carothers [2] and others in 1920's that polymers were structurally long chain molecules. Once this concept of polymers was understood – and finally accepted by the chemistry industry – many of the most common polymers used today were developed in quick succession (see Table 1).

Many of these early plastics were often developed to either replace expensive natural products *i.e.* shellac, or those that were increasingly in short supply *i.e.* elephant ivory. However, the benefits of using plastics for wider applications were quickly seen and rapidly exploited in an ever-widening range of markets. Despite the early exploitation of plastics, the total production by 1950 was only around 1.5 million tons, but the rate of growth since then has been exponential and currently amounts to around 350 million tons per year. Since production of synthetic plastics have begun, it is estimated that 6.3 billion tons of plastics of all sorts have been produced.[3]

The widening use of plastics in every increasing numbers of applications can be appreciated by the approximate 50-fold increase, i.e. from 0.7 kg/person to 45.2 kg/person over the last 70 years. These numbers are based on global population and plastics production figures, so the mass per person will be high for low-income countries and low for high income countries like the UK. A relevant question is therefore are we producing and using too much plastic? It is a question that is being widely discussed by different interest groups recently but is outside the scope of the current discussion.

Although plastics are used ubiquitously in a huge range of applications split across different market sectors, the packaging sector makes up the largest single segment of around 40% of all plastics used. It is partly because of this visibility that packaging plastics are the focus of much of the

Table 1: Year of discovery of major commodity plastics

Year	*Polymer*
1936	PVC, PMMA, polychloroprene (neoprene)
1937	PS
1939	nylon66
1941	PTFE
1942	polyesters
1943	PE (branched)
1944	PET
1957	PP

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current discussions about environmental impacts and calls for bans on using plastics. Even though there are many hundreds of different types of plastics, over 80% of the total use is associated with 5 major plastics – polyethylene (PE), polypropylene (PP), polystyrene (PS), poly(vinyl chloride) (PVC) and poly(ethylene terephthalate) (PET). Each of the different application sectors have differing use patterns of polymer types, so it is important to appreciate that approaches and solutions to plastic use and waste management will not necessarily be the same for any single sector.

As stated above, one of the initial goals of developing plastics was as cheap alternatives to other materials. Since by far the majority of all plastics (~99%) are derived from fossil fuel feedstocks the price of plastics is therefore intimately linked to those of oil and gas prices. Oil prices over the last 10 years have changed unpredictably but has generally decreased reaching an historic low of below US$20/barrel early in 2020. Over the same time period prices for virgin plastics have generally decreased with an approximate 30% reduction for most of the major commodity plastics. Given price competition for virgin plastics, it has put huge pressure on recycled plastic prices that by default includes extra costs due to additional processing compared to virgin plastics. These additional costs do not often match the public perception, who often think that recycled plastics should be cheaper that virgin plastics. This thinking is probably due to attitudes that 'new' should cost more than 'second hand' for most items.

Throwaway Living

DISPOSABLE ITEMS CUT DOWN HOUSEHOLD CHORES

The objects flying through the air in this picture would take 40 hours to clean—except that no housewife need bother. They are all meant to be thrown away after use. Many are new; others, such as paper plates and towels, have been around a long time but are now being made more attractive.

At the bottom of the picture, to the left of a New York City Department of Sanitation trash can, are some throwaway vases and flowers, popcorn that pops in its own pan. Moving clockwise around the photograph come assorted frozen food containers, a checkered paper napkin, a disposable diaper (seriously suggested as one reason for a rise in the U.S. birth rate) and, behind it, a baby's bib. At top are throwaway water wings, foil pans, paper tablecloth, guest towels and a sectional plate. At right is an all-purpose bucket and, scattered throughout the picture, paper cups for beer and highballs. In the basket are throwaway draperies, ash trays, garbage bags, hot pads, mats and a feeding dish for dogs. At the base of the basket are two items for hunters to throw away: disposable goose and duck decoys.

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Figure 1. Image of the first page of a 'Throwaway Living' article from August 1955 edition of Life Magazine.

Disposable Culture

Given the historic drive for plastics to be cheap and more readily available compared to other natural products, it is perhaps not surprising that the concept of 'disposability' quickly became part of the dream. This attitude was highlighted in an article in the August 1955 edition of Life magazine, entitled 'Throwaway Living – disposable items cut down household chores' (see Figure 1). The article begins "*The objects flying through the air in this picture would take 40 hours to clean – except no housewife need bother. They are all meant to be thrown away after use.*" Although written in a chauvinistic era, it clearly heralds a point in history where society had moved away from reuse and repair and transitioned to disposability being the new norm.

The 1955 Life magazine article was published at a time where the number of 'fast food' restaurants were rapidly expanding across the USA, but quickly to other countries. These fast-food establishments exploited the use of disposable packaging as a key approach for their company strategy. The most important of these companies is McDonalds (founded in 1948) who have been very influential in exploiting single-use packaging plastics, including expanded polystyrene (EPS) clam-shell boxes and plastic straws. Some historians have placed a large fraction of the blame of our disposable culture and resulting environment impacts squarely at the door of McDonalds franchises.

The disposable approach to using plastics is of course a linear economy – where plastic is produced, used once and then disposed of at end-of-life (EoL). The service life of plastics however differs markedly depending on both application and type of plastic. Packaging plastics, for instance, typically have an average service life of 6 months, by contrast plastics in the electrical, transport and building and construction sectors have average service lives of 8, 12 and 35 years, respectively. Clearly changes to legislation has immediate impact on packaging plastics, but the changes we impose now on long service life plastics will have impacts for many decades to come. This is particularly important given all the additives incorporated into plastics ie plasticizers, stabilizers, pigments, etc. A particularly well-investigated example is the change in legislation in use of phthalate plasticizers due to their toxicity. However, bans on their use has only happened fairly recently, so some of these plasticizers are likely present in long service-life plastics currently being used. Clearly, consideration for the plastics and additives we use now will be have a legacy for decades to come in such long service-life plastics and will require more careful treatment at EoL compared to short service-life plastics.

Approaches to Waste Management

Our current linear economy of use means that only a small volume of plastics is reused with the vast majority of collected EoL plastics either sent to landfill, recycled or incinerated for energy recovery. Changes in policies for managed plastics across the EU, have led to a decrease in use of landfill but increases in both incineration for energy recovery and recycling (see Figure 2). The figures hide the different national or even regional differences. Wales, for instance, has one of the best recycling rates in Europe, approaching 60% for all materials, much higher than the EU average of 32%.[4] The increasing trend for incineration for energy recovery has led to many new facilities being built across the UK targeting unrecyclable materials. The majority of all plastics that is recycled currently is via mechanical methods, with only a small amount (pilot-plant scale) that is chemical recycled. Despite these managed approaches to EoL plastics, it is estimated that up to 4% of all plastics produced are lost out of the system and ultimately end up in the World's oceans, i.e. up to 12.7 Mt/yr – 9.5 Mt/yr via land sources and 1.7 Mt/yr from shipping and fishing.

As a back of the envelope estimate, given the total mass of all plastics ever produced at a steady 4% loss of plastics per year then approximately 250Mt plastics have been lost to the oceans. This has had a huge ecological impart, which is believed to have caused a reduction to marine productivity of up to 5%.[5] With the global marine economy worth almost US$50 trillion/yr,[6] this is equivalent to a loss of up to US$ 2.5 trillion/yr. Although the issues of marine plastics have been a major focus not only of public attention and scientific research, the impact of terrestrial plastics is most less studied. However, studies suggest that there are up to 23 times more plastics on the land than in the oceans,[7] yet the environmental and economic impacts of these terrestrial plastics are not well understood.

The ecological and environmental impacts of plastics depends not only on their various chemistries, but also their additives as well as their size. Macroplastics, ie pieces of plastic larger than a few millimeters, have noticeable effects on individual animals through entanglement or ingestion often leading to individual fatalities. However, of equal concern are the impacts from micro- and nanoplastics, i.e. pieces dimensionally submillimeter or submicron, respectively. Their effects are the subject of increasing research but are clearly challenging to study for various technical reasons and as such their impact is much well less understood compared to macroplastics. Among the many areas of public concern is the effect of consumption of microplastics particularly as a result of eating seafood. How true then are comments such as, "sea creatures eat plastic, therefore when I eat seafood, I'm eating plastic"? Whilst microplastics are consumed by shellfish, given their habitat and feeding mechanisms they are very well adapted to exude

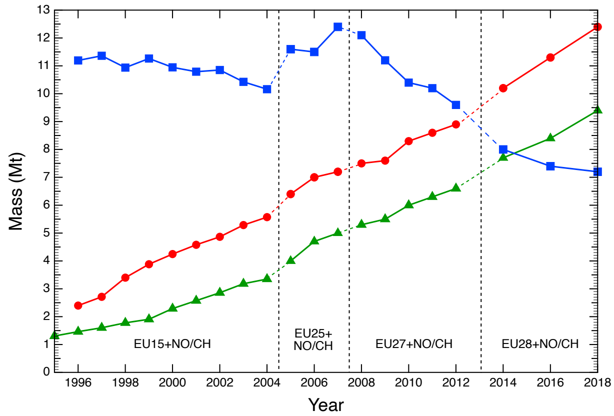

Figure 2: Changes in post-consumer plastic that is landfilled (squares), recycled (triangles) or incinerated for energy recovery (circles) in Europe. Data taken from Plastics Europe annual reports.

out any plastic particles they consume in the same way they do with sand and gravel particles. By comparison the level of airborne microparticles and microfibers in a typical building is hundreds of times higher than found in seafood, so any microplastics we consume will have largely originated from the airborne sources present all the time.[8] Deaths of seabirds and sea animals as a direct consequence of entanglement or swallowing large volumes of macroplastics are well documented, consumption of microplastics by humans has yet to demonstrate any effects and all the plastic particles are simply excreted naturally. Although macroplastic effects on individual animals are easy to demonstrate, the effects that plastics in general or specifically have on whole populations are extremely hard to determine given the complexity and influences on the ecosystems they live in. Given the general concern for plastics effects on the environment, studies of population level effects require significantly more research.

Given plastics in the environment have an impact, who then should take responsibility for the problems caused by these mismanaged plastics? The companies who produce and sell plastics, the plastics processors who produce the products, the companies who sell or use the plastics products, the consumers i.e. the general public, or the EoL companies, ie the waste disposal or recycling companies? Whilst all of these need to be held accountable, the consumers themselves need to shoulder a fair degree of the responsibility. For example, look at any public area after the public have visited and the litter left behind is very noticeable. This wholly inappropriate human behavior is a major factor contributing to plastics polluting the environment. However, regional and national attitudes to litter vary and, in some countries, such as Singapore and Japan, there is very low or near zero litter problems. Why are these countries or regions better than others? The answer to this is complex and relates to a combination of factors that includes economics, legislation and technology, but equally importantly also includes societal values and peer pressure.

Future Challenges

To address the impacts that plastics are causing a number of organizations, such as the Ellen McArthur Foundation and WRAP, have been at the forefront in helping to push through changes in policy in the UK. The *UK Plastic Pack* for instance is an initiative led by WRAP to bring together stakeholders, ie businesses, UK governments, and NGOs to tackle the problems with plastics and create a circular economy for plastics. The initiative, largely focused on plastic packaging, has challenging commitments to be met by 2025. The major goals to be achieved by 2025 are for 100% of all plastic packaging to be reusable, recyclable or compostable, 70% of plastic packaging to be recycled or composted, elimination of single-use plastic packaging and 30% recycled content to be used in all plastic packaging. Other initiatives with similar targets and aggressive timescales have been established in many other countries. For instance, in 2019 the EU Government passed legislation to ban single-use plastics (SUPs) that will come into force across the member states in 2021. This ban covers a small number of SUP plastic products, including plastic cutlery, cotton buds, straws and stirrers. Given the limited SUPs this ban will cover it will be interesting to see what effect this will have on reducing the amount of mismanaged plastics entering the environment. Perhaps because of the strength of feeling to reducing environmental impact from plastics, this legislation unusually was approved by the EU Parliament extremely quickly. The speed that the legislation was approved, has led to questions being raised as to whether it was thought through properly, particularly with regard to the potential impacts to vulnerable groups such as the old aged and disabled who rely on use of these SUPs.

Although the general public's attitudes to SUPs have been driving calls for banning their use in recent years, these attitudes have changed dramatically since the onset of the current coronavirus pandemic. The most obvious sign of this is seen through an increased demand for certain plastics, despite an overall reduction across the whole plastics sector. Obvious increases in demand have been seen for PMMA for all the transparent screens being put up in shops and public areas, as well as PET (and other plastics) for bottles and containers for water and soft drinks, soap and sanitizer fluids and other cleaning and disinfectant products. All products which have been in exceptionally high demand since the beginning of the pandemic. Anecdotal evidence also suggests that some grocery stores have been telling customers their reusable bags aren't welcome and others have been reintroducing plastic packaging to ensure hygiene and security. The most widespread change in SUPs has been the huge demand for plastic personal protective equipment (PPE), i.e. disposable gloves and face masks. Initially the demand far exceeded supply in many countries, not only because the demand was not foreseen, but because initially most of these items were not produced in the countries they were required. Prior to the pandemic, almost no PPE was produced within the UK. To meet the shortfall in imported supplies, some UK companies were able to change production from their normal products to make various PPE.

The extraordinary usage of SUP PPE since the start of the pandemic has however had an unfortunate side effect, with noticeable amounts of litter composed of disposable gloves and face masks. Clearly, whilst social attitudes to SUPs may have changed, the inexcusable littering problem has not changed, and given these SUPs could be potentially contaminated by bacteria and viruses, the littering of these items now provides additional health hazards to the existing environmental problems.

Future Research Focusses

So are the goals set out in initiatives such as the *UK Plastics Pact* going to be achievable particularly given the issues caused by the pandemic? If we have any intention to deal with the impact mismanaged plastic is causing then we have no option but to meet or exceed the targets, but the short timescales are problematic. To reach the goals of course will require developments in technology, but there are identifiable approaches to tackle these challenges. More problematic are the questions of economics, i.e. who is going to pay for the changes, whether society want this to happen and supports the approaches by necessary behavioural changes, as well as what legal and/or political changes are required to make it happen. The complex interplay between these factors and what and how these will need to change is beyond the scope of this paper, but an area that will need to be solved.

Technical Drivers

Looking at the technological drivers built into the *UK Plastic Pack* goals, packaging plastics will have to be either reusable, recyclable or compostable. With regard to the latter, there are still significant infrastructural hurdles to overcome. Compostable plastics only efficiently decompose in industrial aerobic or anaerobic composting facilities. As of 2015, the EU only had the capacity to treat less than 9 Mt/yr of mixed organic waste,[9] only a fraction of which contains plastics that is compostable. There are, however, debates about the effectiveness of composting plastics. If they only partly decompose, they are simply going to form micro- and nanoplastic particulates which arguably are worse that the original plastic products. However, full decomposition can generate organic compounds including greenhouse gases (GHGs) and as such are not ideal byproducts if they add to global warming. Whilst compostable plastics may be part of the future solutions, more immediate gains will come from approaches that exploit either reuse or recycling.

Many studies have shown that recycling is an important way to reduce global warming potential (GWP) compared to landfill or energy recovery disposal. Life-cycle assessments (LCA) for plastic bottles show that to maximise the reduction in GWP you must incorporate a high degree of recyclate in the bottle to maximise the GWP reduction. Indeed, for a 30% recyclate content as demanded in the *UK Plastic Pact* initiative will likely only reduce GWP by 14% for PET bottles using conventional mechanical recycling.[10] At 100% recyclate content for PET bottles, GWP is reduced by 45%, but there are both technical and logistics issues that mean reaching 100% recyclability (at least for mechanical recycling) is hugely challenging. Whilst mechanical recycling methods are well established for treating EoL plastics, much of the recycled plastics is used for products different to that which it was initially intended. For instance, whilst a small fraction of recycled PET (rPET) from bottles will be incorporated back into PET bottles, the majority of rPET is currently used for clothing, fiberfill, industrial strapping, sheets and films and automotive parts.

A significant large fraction of the collected plastics (approximately 30%) cannot be treated by mechanical recycling, either because of contamination ie by food, soil, biodegradable plastics, etc, or because the products are mixed and can't be separated cheaply, i.e. multilayer plastic films or mixed material products. Whilst technical improvements in mechanical recycling coupled with better product design will drive better recycling rates in the future, successful commercialization of chemical recycling will be a very important technology for EoL plastics in the future.[11, 12]

Further up the 'waste hierarchy' in dealing with plastics is reuse. Whilst reuse has been widely exploited for glass bottles, commercial reuse in plastics packaging has only recently being explored in more detail. The reasons for exploring plastic reuse can be appreciated from the example for glass bottles, where GWP is reduced very significantly by up to 72% by repeated reuse.[10] Given the major GWP contributions to producing glass and equally to plastic bottles is their thermal processing, similar significant reductions to GWP can be anticipated for reuse of plastics. Although reuse of plastics offers potential for huge environmental benefits, it remains to be seen whether there is a societal appetite for reuse, particularly for food packaging in the light of the changing societal behaviour patterns caused by the coronavirus pandemic.

Packaging Labelling

With regards to plastics and in particular packaging plastics, are the general public in a position to know how to deal with them at EoL? There are multiple symbol types widely used on packaging currently aimed to help consumers identify and deal appropriately with the used package. Whilst each symbol has a specific meaning, not all of the general public understand what these symbols mean and are therefore not able to decide how to deal with the waste packaging. Would a different approach to labelling and/or waste collection have a bigger impact to waste management and litter reduction? Would a simplification of the label system and/or better education have a bigger effect? Indeed, it raises wider questions about who should be responsible for deciding if something is reusable, recyclable or compostable or not. Should we just have one bin for all plastics and let professional recycling facilities deal with the separation? Or do we go to the extent that some countries have gone, such as Japan, where within different municipalities the onus is on individual householders to separate different items into multiple bins - up to 44 in Kakimatsu[13] - for the various waste, compostable and recyclable materials?

Biobased Plastics

In discussing sustainable plastics, it is important to mention *green* polymers. Are they 'better' than petrochemical sourced plastics? The term *green* polymer is widely but very loosely used and means different things to different people. In one sense it is used to mean bio-based plastics, i.e. plastics produced from renewable, non-fossil fuel sources. It is also sometimes used to mean biodegradable plastics, i.e. plastics that decompose via biological activity. However, simply making polymers from bio-based feedstocks, don't necessarily make the resulting polymers environmentally benign. With sufficient synthetic steps pretty much any of the plastics we are familiar with (eg PET, PE etc) can be derived from bio-based feedstocks, to derive polymers that are indistinguishable from those that are derived from petrochemical feedstocks. Indeed, some polymers we have exploited for decades are now made wholly or partially from bio-based feedstocks (for instance, PET is made in part from ethylene glycol derived from plant feedstocks). Bio-derived feedstocks do make plastic production sustainable compared to their fossil-fuel equivalents. Often true bio-based plastics are chemically distinct from anything derived from petrochemicals. These bio-based polymers can be used as drop-in replacements for fossil-fuel alternatives, examples include poly(lactic acid)(PLA) replacing PET, or poly(butylene succinate) (PBS) replacing PP. Although bio-based plastics are being widely investigated and some are being increasingly used commercially, to date only 2.5 Mt of bioplastics are produced annually ie < 1% of total plastics production. So significant changes would need to be made to move to a fully bio-based plastics economy and remove the reliance on fossil fuels.

Many current bio-based plastics are derived from sugars from plants i.e. sugarcane or sugar beet, or starch from corn, wheat or potatoes. Calculations show that to replace all the PET currently produced by PLA - which requires 3.5t of wheat per ton of PLA[14] - would require the equivalent of approximately 16% of the global annual wheat production. Whilst a hypothetical case, it does demonstrate that appropriate sources of the bio-feedstocks will be hugely important when expanding production of bio-based plastics. Clearly, feedstocks that do not impact food resources such as waste agricultural and marine products, i.e. biomass, are the only viable options to prevent adding to global food shortages.

Conclusions

Whilst there are still important technical issues to resolve to meet any of the sustainability goals, the biggest challenges arguably relate to the complex interplay between societal, political, legislative and economic factors. The coronavirus pandemic will undoubtedly make these issues ever more complicated to resolve. The level of financial borrowing by Governments across the globe to mitigate the effects of the pandemic if nothing else demonstrates that if there is a will, money could be found for necessary investments. Whether similar economic investments could be found to address the plastics issues is yet to be seen, but there are growing calls for post-coronavirus recovery to accelerate global climate change initiatives. However, continuing changes in public attitudes and the economic impact of coronavirus perhaps make achieving pre-pandemic targets in any of the original timescales very challenging. The findings coming out of the current Plastic Research and Innovation Fund (PRIF) projects in addition to future innovation and research activities will be essential to help move forwards in resolving these important issues.

Conflicts of interest

There are no conflicts to declare.

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Session 1: "The Plastics Problem" - Perceptions and Misconceptions

How circular are plastics in the UK?: Findings from Material Flow Analysis

Teresa Domenech,[a] Miguel Casas-Arredondo [b] and Wan-Ting Hsu [a]

Globally, consumption of plastics has increased rapidly, reaching 350 Mt in 2017[1]. Trends in the UK have followed a similar pattern. Total consumption of plastics in the UK is around 6.3 Mt (own estimation), considering plastic products and plastic contained in other products. A large share of this, is disposed as waste. Concerns around the use of plastics and its disposal have emerged linked to inadequate end-of-life management of plastics and increased evidence of important leakage to the natural environment, suggesting the need to better align use of plastics to the principles of the Circular Economy. Lebreton et al[2] estimated that globally mismanaged plastic waste represent 60-99 Mt and estimation of leakage in Europe may be around 3.3%. In the UK, still a large fraction of plastics is sent to landfill (31%) or being incinerated (35%). A number of studies have already been undertaken to quantify plastics flows in the UK. Wrap[3] provides an overall picture of plastic flows in the UK, concluding that better capturing residual plastic flows could provide cost savings in the region of £82 million. A recent study by Eunomia[4] provides detail of plastic flows in key sectors of the economy. All these studies highlight important data gaps and uncertainty. Building on previous contributions, the present study has developed a comprehensive Material Flow Analysis for the UK addressing prior data gaps. The MFA provides detail of sector, waste composition and final destination. The aim of the MFA is to estimate current level of circularity of the plastic system and identify areas of inefficiency and leakage to natural systems. Preliminary findings from the analysis are presented in this paper. This work sets the basis for the definition to measure the impact of alternative intervention pathways at different stages of the plastic life cycle, as future research steps. The analysis has highlighted important data gaps with regards to production, inter-sectoral consumption and plastic waste arisings. Estimations of plastic content in other products (textiles, electronics, etc.) relies highly on assumptions around plastic content. Data fragmentation and lack of consolidation across different databases results in increased uncertainty in the quantification of plastics flows, neglecting important plastic leakage to the environment, and thus better harmonization of production and waste data is needed. Preliminary results from the analysis indicate that a large share of plastic waste is generated by industrial and commercial sectors (51%) while post-consumer waste, from households, also represents a very important fraction of plastic waste (43%). While recycling of plastics has increased, a large fraction of plastics still ends up in landfill or incineration without energy recovery (around 53%) and this is likely to be an underestimation as plastics may also be mixed in unsorted fractions of waste not recovered. The paper concludes with a discussion of main areas of opportunity to increase circularity of plastics in the UK and some recommendations on data harmonisation.

Introduction

Rates of plastic use have grown exponentially since the 1950's, reaching 350 million tonnes (Mt) globally in 2017. In Europe, production of plastics has been estimated at 60 million tonnes in 2018, which is around a 17% of world's plastic production[1]. Most sectors in the economy consume plastics, being packaging, construction, textiles, EEE and automotive among most important applications. The advantages of plastics are many, being a cheap and versatile material, which has increasingly become present in numerous consumer goods, leading price reductions, better protection of goods, enabling trade, preservation of food, reducing food waste or improved health & safety linked to use of disposable plastic products in sectors such as health care. This increased plastic use has raised issues around end-of-life management and waste leakage to natural ecosystems. A large share of plastic products are single-use or have short life spans, leading to increasing volumes of plastic waste. Mounting evidence of the damage created by leakage of plastic waste into the natural environments have raised concerns around sustainability of plastics. This paper aims to contribute to a comprehensive mapping of plastic flows in the UK, using Material Flow Analysis (MFA) as a main methodological approach. The MFA covers the whole cycle of plastic from production of primary polymers and fibres to consumption and end of life of products. It provides detail of sector, waste composition and final destination, and the scope encompasses all main sectors of the economy and all main applications of plastic. The paper has been organised as follows: the Literature Review section summarises current state of the play in the literature with

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regards to the estimation of plastic flows; Methodology describes the methodological approach used and defines the model; the Analysis section summarises key preliminary findings from the research, and Discussion and conclusions discusses implications for circularity from main findings and draws some conclusions and next steps.

Literature review

Growing concerns around the use of plastic and destination of plastic waste have resulted in numerous papers and reports in the area. The literature tends to focus on the destination of plastic waste, plastic entering the ocean and policy measures to increase circularity. MFA has been used in some of the recent contributions to measure the circularity of plastic flows at different levels of analysis and varied scopes.

Geyer et al[5] present an analysis of all plastics ever manufactured world-wide, combining plastic production data with product lifetime distributions for eight industrial sectors. They estimate that 8300 Mt have been produced as primary plastics up to 2015 since the creation of this type of material. From this, 30% is currently in use, 76% (6300 Mt) became plastic waste, and around 9% of which was recycled, 12% incinerated, and 79% was accumulated in landfills or leaked into the natural environment. A yearly approximation is given for 2015 by the same authors, where 407 Mt of primary plastics were manufactured from virgin materials and 302 Mt of plastic waste was generated. Lebreton et al[2] use country-level data on waste management and combine it with distributions and long-term projections of population and gross domestic product. They conclude that between 60 and 99 Mt of mismanaged plastic waste was produced globally in 2015, and this figure could triple to 155 – 265 Mt by 2060. Jambeck et al[6] associate solid waste generation data for 2010 with waste characterization information and estimate that 11.6% of global plastic waste is mismanaged and 1.7% to 4.6% of this waste entered the ocean, mostly leaked through rivers[2,7]. Modelled estimates show that over 0.25 Mt of microplastic particles have been accumulated in the world's ocean up to 2014[8,9].

At European level several recent studies have investigated the flows of plastics in the EU economy. Kawecki et al[10] use a probabilistic approach through Bayesian distributions to conduct an MFA for seven key plastic polymers in Europe, where PP represents the largest share of consumption, followed by LDPE, PET, HDPE, PVC, PS and EPS. Based on data of plastic mass flows and average plastic contents of semi-finished and final products, Van Eygen[11] report that about 1.3 Mt of total primary plastics were consumed in Austria in 2010, where 1.1 Mt were produced locally. Roughly one third of the consumed amount materialised as net additions to stock, and about half of this increase occurred in the construction sector, while packaging waste comprised around half of the total post-consumer waste. The Danish Environmental Protection Agency[12] provides a preliminary assessment of plastic flows in Denmark for 2016, based on existing data. They report that no synthetic polymers were produced in that country, and the difference between exports and imports resulted in a primary plastic consumption of 0.61 Mt. Landfill and incineration were reported as the prevailing waste treatments in Europe for all polymer types across all industry sectors[10], and a recycling rate of 31% and 22% were calculated for Austria and Denmark, respectively[11,12].

For the UK, recent years have also seen an increase in the number of reports studying plastic flows. Eunomia[13] provides an estimate of plastic packaging waste generation and suggests that current reported recycling rates for plastic packaging are overestimated almost by a factor of two. Root causes of this lie in how current EPR systems are organised, which create incentives to under-report plastic packaging put on the market and distort recycling rate calculations as the ratio from plastic packaging put on the market (in clean and dry form) and waste volumes sent to recycling (with higher moisture and cross-contamination). Also, Eunomia[4] produced a report tracing plastic flows covering the main sectors of plastic application (for macro-plastics) and estimated the release of micro-plastics into the environment from tyre wear and textiles. WRAP[3,14,15] has produced a number of reports focusing on plastic waste and plastic waste treatment in the UK. While much of the focus is on plastic packaging, the reports also provide some data on arisings and waste destinations of non-plastic packaging. Although the scope of these studies is similar to the current research, they do not provide a full life cycle overview of plastic flows. Methods and calculations also differ, especially with regards to the analysis of plastics content in products.

Methodology

Material Flow Analysis (MFA)

The methodology is based on a static Material Flow Analysis (MFA). MFA is a systematic analysis of the interactions between natural and socio-economic systems in a specific time and space boundary governed by the mass conservation principle[16]. MFA provides a description of flows and stocks in a system and, thus, helps to identify areas of potential inefficient use of resources. In the context of the circular economy, MFA has been used to assess the degree of linearity or circularity of a system by tracking the flows of materials from extraction to final treatment and disposal. Typically, MFA of a specific material covers the full life cycle from primary extraction, to manufacturing, consumption, recovery and disposal[17].

System description

In this study we follow the flows of all plastic polymers from initial production of plastic polymers and fibres to final disposal and treatment. The system considers six main stages: production of primary polymers and fibres, manufacturing of semi-finished products, manufacturing of plastic products and plastic containing products, consumption by sector, waste collection and waste treatment. Trade movements, imports and exports, are considered at every stage of the plastics life cycle. Figure 1 describes the system boundary of the study. The temporal boundary is 2016, as the last most up-to-date and comprehensive statistical data year. The geographical boundary is the UK as a whole although data has also been compiled at local and regional levels to assess degree of completeness of national-level data. From the production side, the scope of the study considers the production of primary polymers which will then be transformed into semi-finished products. Both semi-finished products and fibres are then transformed into plastic and plastic containing products. Consumption is calculated as the addition of all plastic products and plastic containing products manufactured in the UK plus net imports. Although there would be a small fraction of material lost at different stages during initial production of primary polymers and, more importantly, during manufacturing processes, these have been computed in the waste stage which differentiates between household (HH) post-consumer waste and industrial, construction and commercial waste. The consumption stage differentiates application of plastics by main sectors. A sector of 'other´ plastic products has been defined to group other smaller in share product categories. Imports and exports have not been computed at the consumption stage as are reflected in the trade of finished products. For the estimation of plastic contents in different product categories, data from previous reports[18-24] has been combined with own estimations based on market data (amazon, manufacturer websites, Environmental Product Declarations, etc.). The end-of-life stages have been divided between waste arisings (i.e. waste collection) and waste treatment, which indicates how the waste has been managed, what methods have been used for its recovery (i.e. recycling and energy recovery) and how much has been incinerated or disposed of without recovery (i.e. landfill). Similar to what was done for plastic-containing products, plastic fraction coefficients have been estimated from different academic and industrial sources[25-32] for the estimation of plastic fractions in waste types by NACE sector. A number of uncertainties arise from these estimations as, for example, plastic content in textiles or EEE have grown considerably in recent years. Plastic fraction in waste is also a source of considerable uncertainty in the study as there are likely to be important local and regional differences in waste characterisation by sector and region.

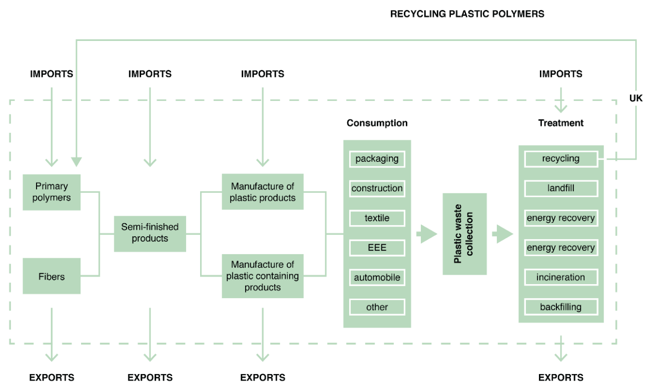

Figure 1: System boundary of the study.

Data sources

Main data sources in the analysis have been collated in the table below by MFA stage.

Table 1: Key data sources by MFA stage.

Life-cycle stage	Concept	Eurostat database
Production and Consumption	Primary plastics	Sold production, exports and imports by PRODCOM list (NACE Rev. 2) - annual data
	Fibres	
	Semi-finished plastic products	
	Finished plastic products	
	Plastic-containing products	
Disposal	Waste generation	Generation of waste by waste category, hazardousness and NACE Rev. 2 activity
	Waste import/export	Trade in recyclable raw materials by waste
	Waste treatment	Treatment of waste by waste category, hazardousness and waste management operations

Analysis

The overall MFA for the UK is represented in the Sankey Diagram below (Figure 2). The material flow diagram provides an aggregated representation of the plastic system in the UK, covering both the production, consumption and end-of-life phases. The analysis of each of these phases is briefly reported in the sections that follow.

Plastic production in the UK

In the UK, primary plastic polymers and plastic fibres are dominated by imported materials. Over 50% of primary polymers were imported, with negligible internal plastic fibre production. Around 3.6 Mt of raw materials were used for the production of semi-finished products. Semi-finished products group around 50 different product categories of semi-manufactured goods that will then be incorporated into different categories of finished products. Trade of semi-finished products results in positive net imports of almost 0.5 Mt.

In the case of finished manufactured products, the analysis distinguishes between plastic products (where the totality or a larger part of the product is made of plastic) and plastic containing products, which represents all other product categories with an important plastic fraction. Plastic-only products include around 110 categories of plastic products. Production of final manufactured plastic products in the UK is around 4 Mt, while total consumption (production + imports -

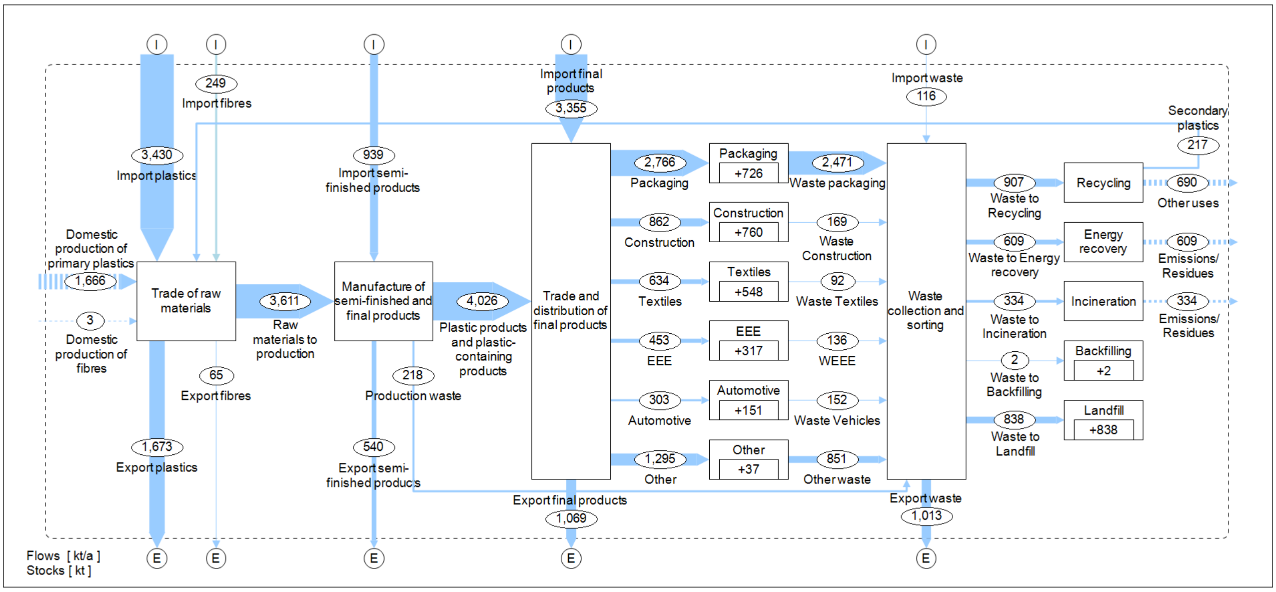

Figure 2: Material flow diagram of plastics in the UK for 2016.

exports) is estimated at 6.3 Mt. Endogenous production clearly dominates for plastic products, especially in the categories of packaging products, with an important UK production of plastic bottles and flasks, and construction plastic ware products.

For the calculation of plastic contained in other product categories, over 374 product categories were considered. Assumptions based on the literature, industrial and commercial reports were made to estimate plastic fraction for each product categories. These include textile products, luggage and handbags, footwear, paper products, paints and varnishes, tools, EEE and other electronic and IT equipment, specialised instruments and equipment, machinery, motor vehicles, sports goods, toys and furniture. Total plastic contained in these products has been estimated at 2.09 Mt. All these categories are clearly dominated by imports which represents around 94% by weight of total plastic contained in these products. UK production is only relevant in the case of motor vehicles (0.16 Mt), paints and varnishes (0.18 Mt) and electrical equipment (0.11 Mt).

Consumption of plastic in the UK

The consumption stage considers UK inward plastic applications by sector of activity. As shown in the material flow diagram above (Figure 2), leading sector of plastic applications are packaging (33%) and construction (10%), followed by textiles (7%), electronics (5%) and automotive and transport equipment (4%). All other applications across different sectors have been grouped in 'others' (15%), which includes among others agriculture plastics (see Figure 3 below).

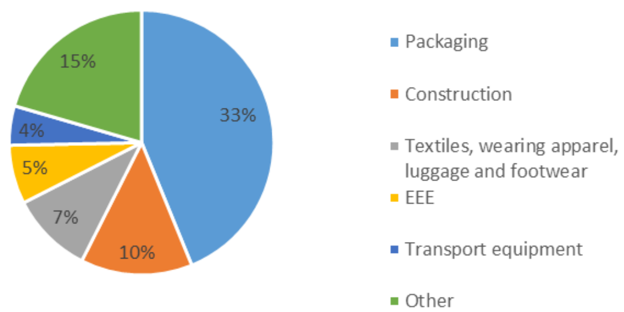

Figure 3: Plastic consumption by sector in the UK.

In the case of packaging goods, most consumed applications include plastic bottles and plastic caps, capsules and other closures. Applications in construction include windows, doors and their frames and plastic shutters and blinds. Although the study did not consider the specific polymer composition of the products, building on the literature[10], it is possible to infer dominance of PP, PET and PE for packaging goods and PVC for construction applications.

The analysis also shows important additions to stock for plastic applications. This is especially important for the construction sector, as one would expect, and also for textiles, EEE and automotive. However, the analysis also computes around 25% additions to stock in the case of packaging. This can represent packaging of goods that are still in inventory but also reveal possible leakages of plastic packaging to the environment.

End of life of plastics in the UK

The end of life of plastics in the UK provides a good overview of the degree of circularity of plastic flows. The calculation of plastic waste arisings considers the plastic fraction for each waste type generated by NACE activity. The total plastic waste arisings are estimated at 5.3Mt, from which around just under 50% corresponds to plastic packaging. This figure is considerable higher than previous estimates (see[3]) which estimate plastic waste arisings at around 3.3 Mt (for 2013). This is partly explained by the scope of the study (as this one includes sectors like textile and health care), which were not considered in previous studies, as well as methodological differences, mainly linked to uncertainties in the calculation of plastic content in products and different plastic fractions in waste. Plastic applications were data available is better, such as packaging, provide similar estimates. Commercial and HH waste make up the large majority of plastic waste, followed by manufacturing, construction and agriculture (see Figure 4).

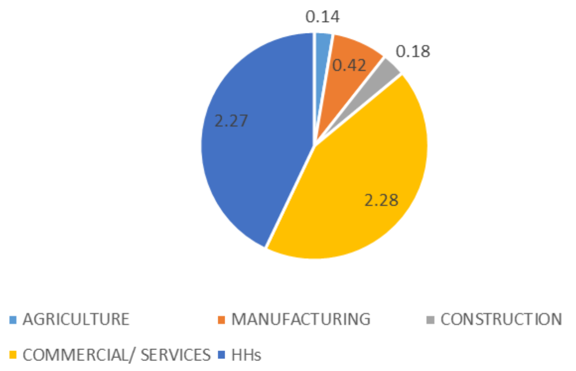

Figure 4: Waste generation (Mt) by waste source.

Waste undergoing treatment in the UK amounts to 2.7 Mt. These preliminary results report a very important difference between waste generation (current estimate at 5.3 Mt) and waste treatment (2.7 Mt), which may be explained by a number of factors: 1) waste treatment includes only waste treated in the UK, however a fraction of the waste will be exported to third countries for further processing (as discussed below) and therefore is not included here; 2) cross-contamination and differences in moisture content may explain differences between waste arisings and waste entering treatment operations; 3) treated waste will have gone through processes of sorting and drying, which would have reduced cross-contamination and volume; 4) another fraction of plastic waste may be included in other waste categories entering treatment and not accounted as plastic waste; 5) sectors with documented increasing use of plastics, such as construction, may result in accumulation in stock which will become waste in the future, and this may have led to overestimation of plastic waste arisings in sectors such as C&D and EEE and 6) a fraction of plastic waste will be leaked to the environment or lost in transit.

From the plastic waste entering treatment, around 34% is sent to recycling, followed closely by landfill (31%) as main route for non-recovery disposal. Energy recovery operations (R1) is after recycling the most common recovery route (at around 23%). Incineration of plastics is the option for around 12% of the plastics entering treatment (see Figure 5).

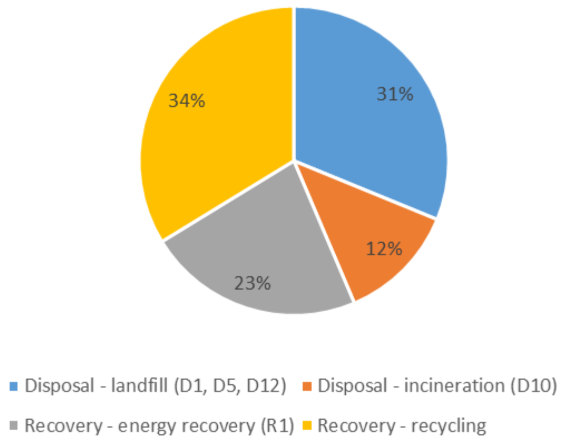

Figure 5: Waste treatment by waste managament operation.

An important fraction of plastic waste is sent for recovery outside the UK. This is segregated plastic waste, which complies with Waste Shipment Regulation requirements[33]. Net exports of plastic waste account for just under 1Mt (0.9 Mt), according to EUROSTAT data, which is just slightly higher than the plastic waste exports computed in UN Comtrade database (0.8Mt). For the year of study, China and Hong Kong are still the main two destinations of plastic waste both by mass and value, but Malaysia and Vietnam have also evolved as major destinations of UK plastic waste. In the EU, the Netherlands and Germany are also very important destinations of plastic waste, mostly as feedstock for overcapacity of energy recovery operations in those countries.

Circularity and secondary markets

Preliminary findings of the analysis indicate that around 0.9Mt of plastics may enter recycling processes. Considering recycling losses of around 10-20% and a recycling efficiency of 90-95%, available secondary plastics for reprocessing could be in the region of 0.6-0.8 Mt. This is less than 10% of the total plastic consumed and around 6% if we include semi-finished products. This is close to other recent estimates such as EEA[34] which estimate that use of secondary plastics in the EU economy would be in that region.

Discussion and conclusions

Preliminary findings from the MFA above point to a largely linear plastics flow in the UK. Plastic waste sent to recycling processes makes only a small fraction of total plastics consumed (14%) and considerably smaller than what reported recycling rates seem to suggest. Plastic recycling rates are calculated for the packaging fraction and based on products on the market, providing an artificially larger percentage of recycling[13]. Around a million tonnes of plastic waste is exported; some of which may be recycled but traceability is difficult to follow. Evidence also suggest that plastic waste exports can be considerably higher considering exports of other waste which may contain plastic fractions (e.g. WEEE).

Recycling rates of plastics are not straightforward to calculate as plastic content by type of product differs and there is a lack of harmonised methodologies to monitor plastic waste. Only for the UK, recent estimates of plastic arisings and recycling rates differ. Our study provides an estimate of plastic waste arisings considerably higher than the figure estimated by WRAP[3]. This can be explained through differences in the scope and assumptions around plastic fractions in products. There is also considerably uncertainty with regards to the final destination of plastic waste. While traceability of plastic packaging subjected to Extended Producer Responsibility schemes is better monitored, plastic fractions in other waste streams are more difficult to trace, possibly leading to overestimation of plastic recycling.

The difference between plastic consumption (6.3 Mt), waste arisings (5.3 Mt) and plastic waste treated (3.8 Mt considering exports) estimated for the UK, is high but also consistent with other studies published at the EU level[34]**.** The gap between waste arisings and waste treated is partly the result of how data is collected and the fact that segregation and drying processes take place between different fractions that are sent to treatment operations.

In terms of plastic waste destinations, the UK estimates are also consistent with EU destination of plastic waste. The share of plastic waste sent to landfill is both 31% for the EU and the UK, while energy recovery in the UK is significantly lower than the EU average (39%). This is partly explained by differences in the treatment capacity mix between the EU and the UK, with important energy recovery capacity in Northern European countries.

Increasing recycling rates face several barriers ranging from: low profitability of plastic recycling, due to weak demand for recyclate plastic; high uncertainty linked to volatile price of primary plastics; and technical difficulties in managing and dealing with complex composite designs and the wide range of plastic polymers on the market. This leads to a loss in the material integrity and value of plastics at the end of their first life, which has been estimated as an economic loss of between EUR 70-105 billion annually[34]**.**

From a circular economy perspective, solutions to plastic waste should consider simultaneously: material traceability; design of products; end-of-life management; and final treatment. EU policy respond to increasing concerns around plastic waste led to the adoption, in 2018, of the European Strategy for Plastics in a Circular Economy, which lays the foundations for better design, production, use and recycling of plastics. Among its key measures, it introduces a binding target for all packaging to be recyclable by 2030, and also increases the target for plastic waste recycling to 50%. The current BREXIT process poses questions around the commitments for plastic waste, but DEFRA's report 'Our waste, our resources: A strategy for England'[35] suggests that the UK will match EU commitments in this area with the aim to eliminate 'avoidable plastic waste' in the timeline of the 25-year Environment Plan. This is partly supported by the 'UK Plastic Pact' which proposes a collaborative framework across supply chain stakeholders to achieve very ambitious targets for plastic packaging including increasing recyclability (100% reusable, recyclable or compostable), improving recycling (70% high quality recycling) and promoting use of secondary markets through recycled content targets. This certainly provides incentives into the right direction to improve circularity but also requires investments to increase recycling capacity, further work in the development and consolidation of a secondary market for recycled plastics, and further action to improve end of life of biodegradable and compostable packaging.

To conclude, the analysis has shown that there are still important gaps in measuring the circularity of plastic flows. Data gaps increase uncertainty in the calculation of plastic consumed, additions to the stock and waste arisings. Treatment data is based on inputs to the different treatment routes but outcomes of treatment processes are not well understood. The circular economy for plastics requires a comprehensive and holistic approach to rethink the production (including sources of feedstock), use, recovery and final disposal, to create systems that minimize not only resource use, but also importantly, environmental impact of the overall system.

Conflicts of interest

There are no conflicts to declare.

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How much plastic do we use and can we live without it?

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Plastics play a vital role in modern society. But just how much plastic do we, as consumers, accumulate at home over time and dispose of as household waste annually? Based on the best information available, we put some numbers on the direct plastic footprint of UK households in various forms and applications such as packaging, dwellings, vehicles, electrical and electronic equipment, clothing and footwear and unveil the evolving trends over the last decade. We also quantify the plastic waste flows in three counties in the South West of England, Cornwall, Devon and Somerset, focusing on the fate of plastics. The household footprint unpacks the extent and scale of plastics use in our everyday lives, pointing to the impossible mission of living without plastics. The ExeMPLaR household plastic footprint tool provides a detailed bottom-up method to quantify household stocks and flows to determine pathways and monitor regional trends and changes over time. This can help reduce our plastic footprint and better predict and manage plastic wastes arising.

Introduction

Plastics play a vital role in modern society and increasingly so. But they also have caused a wide range of problems, from emissions of climate altering greenhouse gases (GHG) during production[1], leaching of potentially toxic substances during use[2], to releases of ecosystem damaging macro- and micro-plastic wastes to the environment at end-of-life[3]. These problems are partly due to the types and sheer volumes of plastics we use and partly to the ways in which we manage plastic as a material.

Tackling the enormous challenges posed by plastics may seem a daunting task. Different approaches, including technological and social/behavioural, have been employed in recent years. The ExeMPLaR project aims to create Circular Economy (CE) based solutions systematically to redesign the current plastics system from a regional perspective. Three key potential solutions/interventions to be tested in ExeMPLaR include using regionally and locally available raw materials such as biomass in plastics production, closed-loop manufacturing utilising waste plastic materials collected locally, and community based behavioural change initiatives such as “plastic free” towns.

A good quantitative understanding of the stocks and flows of plastics is the basis to design a better, future circular plastics system. However, detailed quantitative information is scarce and very patchy at best, particularly from a consumer point of view. Top-down information is available from the plastic industry on the volumes of different types of plastics used in different sectors[4]. But it is difficult for consumers to relate the high level numbers to everyday consumption. This can hinder the effectiveness and efficiency of behavioural initiatives and local and regional waste management as well as affect other important environmental goals[5].

Our paper aims to address some of the fundamental questions that need to be answered. These include: 1) just how much plastic do we, as consumers, accumulate at home over time and in what forms does plastic come into our homes? 2) how much plastic do we dispose of as household waste and where does it go after we throw it in the bin or recycling sack? And 3) can we really live without plastic?

To do this we will estimate, from bottom up, the household direct plastic footprint (HDPF) in the UK covering various forms and applications such as dwellings, vehicles, textiles and packaging, and unveil the evolving trends over the last decade. This will provide a holistic picture of the extent and scale of plastic use in our everyday lives, helping to inform efforts in reducing plastic consumption and waste generation. We also examine the local authority household waste data to highlight possible regional variation in the quantity and fate of plastic waste.

Methods

We define the household direct plastic footprint (HDPF) as the stocks in and annual flows of plastic materials in and out of homes in the UK. The stocks in a given year are calculated as the average quantities of plastics in homes at the end of that year. The inflows and outflows in a given year are calculated as

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plastics brought into homes as products and packaging and plastic waste taken out of homes, respectively.

The "direct" nature of the footprint in our study means that only the plastics physically entering or leaving homes are considered while plastics used in services or the supply chains of products consumed by households are excluded.

A very diverse set of available datasets, including national statistics and surveys, industry reports, academic research and proprietary information, are used to derive the key parameters needed to calculate the HDPF. These parameters mainly include quantities of products consumed and/or owned by households and their physical characteristics such as mass, material composition and lifetime.

We try to cover a comprehensive list of stuff that households use or own. This was grouped into a few main categories of products (see Figure 1): dwellings, vehicles, electrical and electronic equipment (EEE), textiles (including clothing, footwear and other types of household textiles), packaging and other home (including, e.g., furniture and homeware).

Figure 1. Main categories of household products used in the direct plastic footprint estimates

Data on household waste collected by local authorities in Cornwall, Devon and Somerset was used to estimate the plastic waste arising and different waste treatment pathways for these three counties in the South West of England. Assumptions are made regarding the share of plastic waste recycled in the UK and exported and the rates of leakage to the environment for different methods of collection (e.g., kerbside collection, household recycling centres etc).

Results and discussion

The HDPF for an average UK resident between 2009 and 2018 is shown in Figure 2. Plastic stock increased slightly from 460 kg/person (1,104 kg per household) in 2009 to 473 kg/person (1,136 kg per household) in 2018. More than half of the stock is in dwellings (mainly wall and floor insulation and window frames), followed by vehicles which accounted for nearly 20%. Plastic stock in EEE is dominated by large household appliances such as fridge-freezers, washing machines and electric cookers (see Figure 3).

The plastic flows are gradually decreasing, mainly because of decreases in the "other home" category. This in turn is due to the simplistic way we estimate the mass and plastic content of retail items other than food, drinks, textiles, personal care & hygiene and EEE. Plastics in food & drinks packaging are dominated by a few types of products such as non-alcoholic drinks, dairy products, fruit & vegetables and meat & fish.

The types of plastic polymers found in different products vary significantly. For example, most polymers used are Extruded Polystyrene (XPS), Expanded Polystyrene (EPS) and Polyvinyl Chloride (PVC) in dwellings, PolyCarbonate (PC), Polyphenylene Sulfide (PPS) and PolyPropylene (PP) in vehicles, and Polyethylene Terephthalate (PET), High-Density Polyethylene (HDPE) and PP in packaging.

It should be noted that these plastic footprint estimates are preliminary as there are a lot of data gaps and assumptions made. A key data gap is the evolving plastic content of durable goods such as vehicles and EEE. In our calculations, data on the plastic content of these products are often outdated and only valid at a point in time. As plastics are increasingly used in these products due to light-weighting, their plastic content is expected to increase over time. In addition, the types of EEE included in our calculations do not cover the full range of products due to data availability, especially for ones rapidly growing in number such as smart devices. Therefore, the HDPF values for more recent years are likely to be underestimated. Another key gap is furniture in terms of ownership, sales volumes and material composition. Further research will be needed to refine these input parameters.

Plastic waste arising in 2018 is estimated to be 71, 63 and 61 kg/person for Cornwall, Devon and Somerset, respectively. It appears that plastic waste per capita in Cornwall is slightly higher than the national average while that in Devon and Somerset is ~10% lower. The fates of plastic waste show large variations in the three counties (see Figure 5), mainly because of different waste infrastructure in place. For example, most of the non-recyclable waste goes to Energy from Waste facilities in Cornwall and Devon but is landfilled in Somerset. In general, quantities of plastic waste that are recycled or reused in the UK tend to be very limited, with higher amounts exported. In addition, it is not clear whether and to what extent plastics in some categories of waste (e.g., EEE) are recycled.

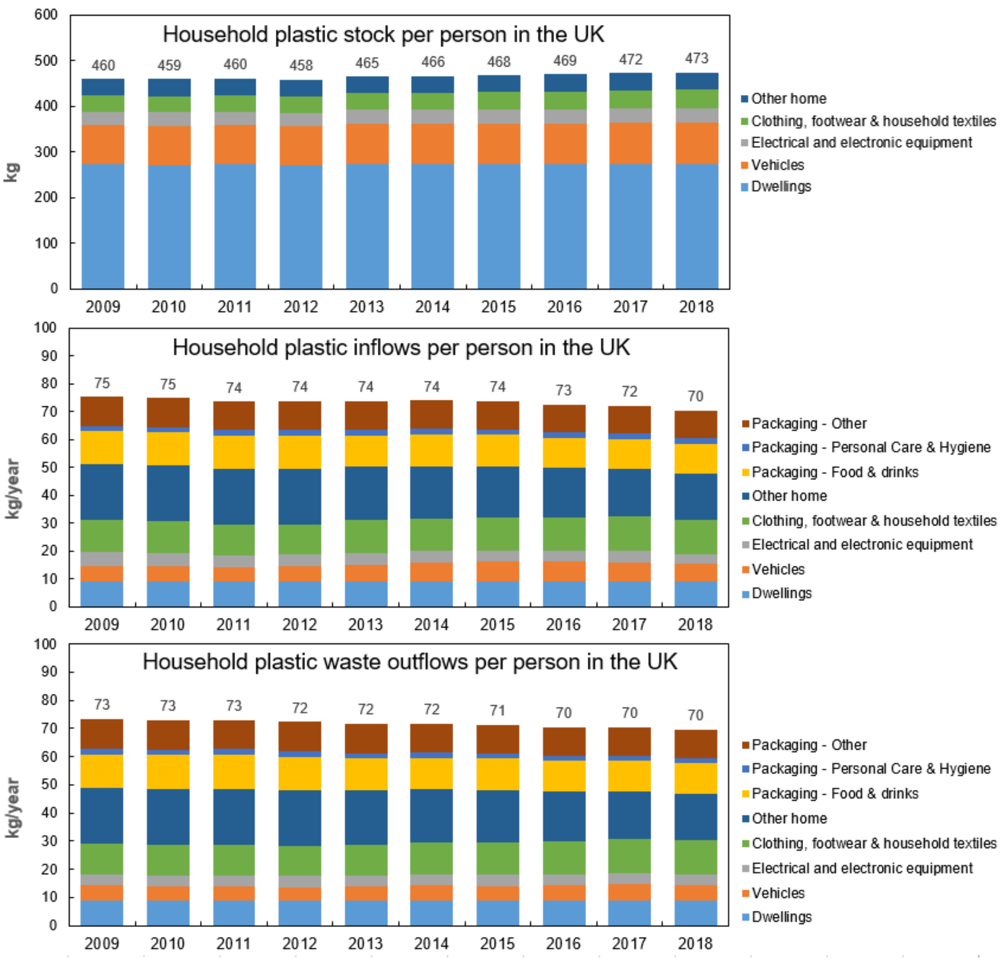

Figure 2. Household direct plastic footprint in the UK

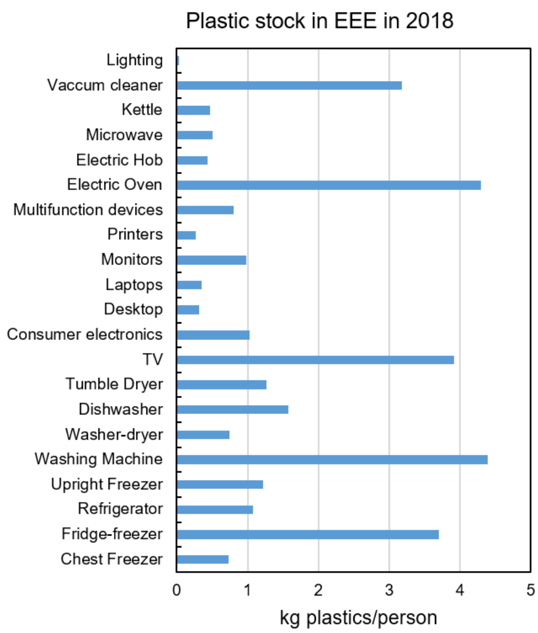

Figure 3. Household plastic stock in EEE in 2018

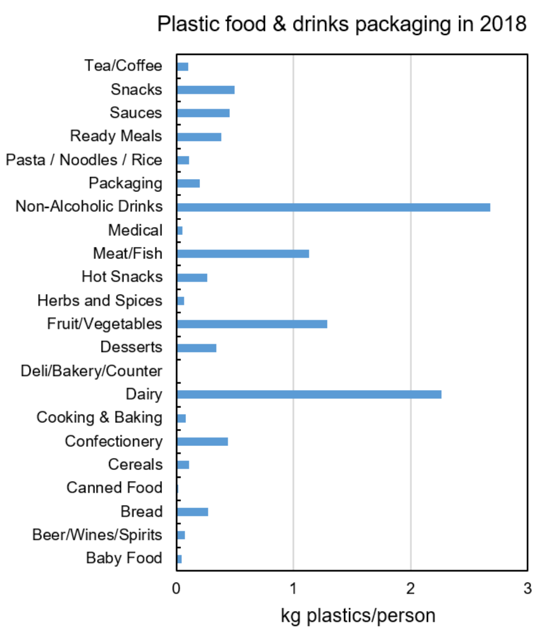

Figure 4. Household plastic food & drinks packaging use in 2018

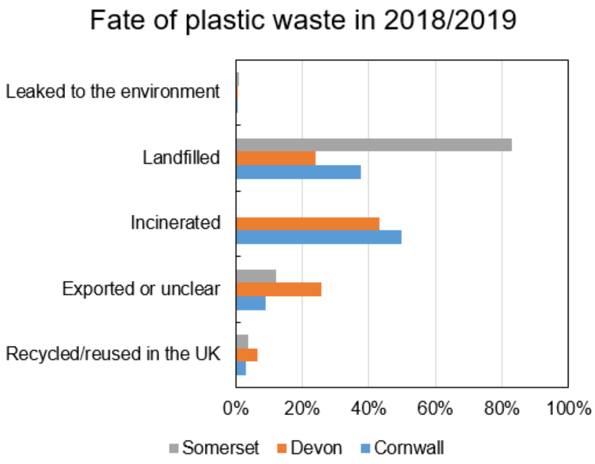

Figure 5. Fate of household plastic waste collected in 2018/2019 for Cornwall, Devon and Somerset (including the plastic components of all waste streams)

Conclusions

To build future circular economy plastic systems and higher value loops requires systemic and systematic approaches to the design, labelling, collection and recovery pathways for such plastic products. We have pieced together all publically available information as best we can to come up with a whole picture of the direct plastic footprint of UK households in quantitative terms. We find that the current UK household plastic footprint is so extensive, varied and large that it is simply impossible to live a modern life without plastics. The ExeMPLaR household plastic footprint tool provides a detailed bottom-up method to quantify household stocks and flows to determine pathways and monitor regional trends and changes over time.

Approaches to circular economy and plastics have tended to focus on single use items and micro and macro plastics in the environment. Public concerns and calls for action have often advocated plastic-free futures or avoidance and reduction in high visibility items such as plastic bags. Whilst these are hugely important they can disguise many other sources and uses of plastics that pervade everyday life, such as household white goods, vehicles, textiles and building products such as windows. These represent sizeable stocks of plastics and also give rise to substantial flows on top of waste plastic packaging. Collectively the majority of household plastic waste in the South West region is incinerated, landfilled or exported – only a small proportion is recycled or re-used within the UK and even less in the region.

The findings from this work illustrate the problem of making claims, or setting targets, for plastic-free towns or houses. Whilst an excellent campaigning message, it is questionable whether this is feasible or even desirable. To replace plastic with alternative materials would lead to different environmental impacts, some of them worse than using fossil fuel plastics. There are multiple ways that avoidable, hazardous and short life plastics and products can be avoided, reduced and replaced although these should each be judged on scientific evidence in terms of their costs and benefits and an overall vision for a future regional circular plastics system.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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Buy the product but rent the packaging – making reusable plastic packaging mainstream

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Plastic waste from single-use packaging amounts to an estimated 2.26 million tonnes pa in the UK alone (1). The introduction of reusable packaging systems has the potential not only to significantly reduce plastics waste but also, when used under the right circumstances, reduce the overall environmental impact of the packaged product. This paper discusses the interdisciplinary research conducted as part of a proof of concept study on 'Reuse' as part of the UKRI funded projct *Plastics: Redefining Single-Use* at the University of Sheffield and proposes future study.

Introduction

That packaging should be recyclable, recoverable, and/or reusable has been part of EU and UK regulations since 1996 (2). To date, reuse has largely been limited to secondary packaging (e.g. plastic crates used to deliver fresh produce to stores), some primary packaging (e.g. bottles for beverages) and niche systems such as refills made available in zero-waste shops. More recently, the European Commission has developed a strategy for plastics in a circular economy (3) and voluntary agreements the UK Plastics Pact and the New Plastics Economy Global Commitment have been launched (4,5). These require signatories to agree to make packaging 100% recyclable, reusable or compostable by 2025 with specific targets for the investigation, and implementation of reusable packaging systems.

To meet these commitments, the question: *'What is required in order to make reusable plastic packaging systems mainstream?'* needs to be answered. In this paper, barriers to, and facilitators of reuse are identified from both technical and behavioural perspectives. Products where consumers are most likely to want to reuse the packaging are determined and reuse behaviour and attitudes to reuse are explored. Plastics are compared to other materials using life cycle analysis for single-use and reusable containers for a food takeaway scenario, and a literature review has been performed on the suitability of plastics materials for reuse systems.

Principles from this work of analysing behaviour, environmental impact and polymer design can be used to codesign a universal packaging concept independent of branding and involving cooperation with multiple stakeholders. The containers used in such a system could be owned by a pool of companies, consumers merely borrowing them for the lifetime of the product, hence the title; Buy the product but rent the packaging.

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Methodology

Reusable plastic packaging was identified as one of three proof of concept studies (PoCs) during a series of workshops involving a broad range of external stakeholders at the start of the project *Plastics: Redefining Single-Use*. Stakeholders agreed that the examination of past and current reuse systems would provide an insight into development of new systems (Part 1). They also wanted to know which products consumers would be willing to reuse the packaging of, and what level of wear after multiple uses would be acceptable to consumers (Part 2). Takeaway food packaging was identified as a good sector to investigate as waste from on-the-go food packaging is recognised as a problem area (Part 3). Finally it was agreed that the best plastic material for use in reusable packaging needs to be identified, taking into consideration durability and the potential for contamination of the packaging and the product from one use cycle to the next (Part 4). This study concentrates on primary (consumer) packaging.

Definitions

Packaging is defined in European (and hence current UK regulation) as follows;

'packaging' shall mean all products made of any materials of any nature to be used for the containment, protection, handling, delivery and presentation of goods, from raw materials to processed goods, from the producer to the user or the consumer (6). In other

words, packaging is a container used for the purposes of selling a product.

'reusable packaging' shall mean packaging which has been conceived, designed and placed on the market to accomplish within its lifecycle multiple trips or rotations by being refilled or reused ***for the same purpose for which it was conceived*** (7) This definition does not cover packaging which has a secondary use e.g. a plastic confectionary box which can then be used to store paperclips.

In academic literature, grey literature and social media, there is little consistency in the terminology used for reusable packaging. The terms 'reuse' and 'recycling' are often used interchangeably, and when used in line with the EU definition above the term reuse can cover a multitude of different product delivery systems. 'Reuse' and 'recycling' are also often used by the general public for the repurposing (or 'upcycling') of containers (e.g. a coffee jar used to keep pencils in). While repurposing is undoubtedly better than sending the object straight to disposal, and also avoids the purchase of a brand-new item, it is not sustainable at scale and does not fall within the EU definition of reusable packaging. A list of definitions of the different kinds of use was therefore drawn up to be used within the proof of concept study. This builds on work published by the Ellen MacArthur Foundation in June 2019 (8).

The definitions of different formats of use used within this study are therefore;

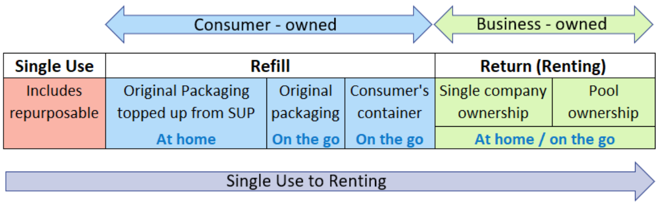
Refill - the empty packaging is filled with the same product either by the consumer purchasing a single-use refill pack - **Refill at home** or by taking the original packaging (or their own container) to a store to be filled - **Refill on the go**. The ownership of the packaging lies with the consumer.

Return - once empty, the packaging is returned to the manufacturer or a processor to be cleaned and refilled either **Return from home** - it is collected from the consumer or **Return on the go** - the consumer takes it to a drop-off point. The ownership of the packaging remains with the brand-owner or a 3rd party i.e. the packaging is rented by the consumer.

Single-Use - Single-use packaging is packaging which is used only once for its intended purpose then disposed of or recycled. This includes ***Repurposable*** packaging - single-use which can be used for a secondary purpose, either by design or at the initiative of the consumer. Repurposing is not seen as a form of reuse within the study. However, the general public considers it a form of reuse, so this has to be included when performing citizen-based research.

The rank order scale in Figure 1 is based on the anticipated amount of waste packaging produced decreasing from left to right. For example, refills at home still require a single-use packaging component for the purposes of the refill, so have been placed to the right of single-use. Refill on the go has been placed to the right of refill at home, because the amount of secondary packaging waste created using this format of refill is less (or next to zero depending on the exact method used).

Figure 1.



Single-Use to Reuse Scale in decreasing anticipated packaging waste from left to right. Note: SUP = single use packaging/plastic

Note that whether an item is recyclable or not has not been considered here.

1. Case study of an existing reuse model - Doorstep Milk Delivery

Focusing on a traditional example of reuse, we reflect on the potential barriers and enablers to making reuse mainstream. Doorstep milk delivery, the milkman* model, highlights that the transition from reuse to single-use, and therefore a potential reverse, is entangled in a complex network of technical, social and economic factors.

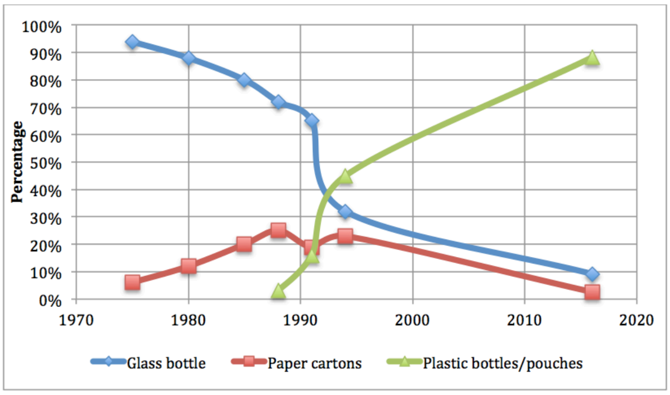
The Returnable Glass Bottle

Prior to the widespread use of bottles, many households relied on a local distribution system of a horse-drawn cart carrying milk churns from which customers' jugs were filled (9). Technical advances in glass bottle manufacture in the late nineteenth century provided a container that was relatively strong, keeping the contents (milk) fresh and free from contaminants (10). These bottles were returnable out of necessity due to the high cost of manufacture, which was practical when distribution was localised - retailers implemented systems of delivery and collection, as well as using branded bottles in order to maximise return rates. Crucially the use of single-use lids (originally card, then crimped foil) meant that the bottles had limited repurposing potentialpotential as they couldn't be resealed.

The subsequent expansion of large dairies with bottling plants signalled the end of the small dairyman. As Vaughan et al. highlight, "the milk bottle became the key mechanism for pasteurised milk distribution to schools and households, since bottling plant technology and pasteurisation equipment could be housed together" (11). By 1975, 94% of milk in the UK was delivered in glass bottles. Since then, the UK market share has declined to approximately 9% in 2016 and to as low as 3% in 2018 (12). Glass bottle sales experienced a significant decrease between 1991 and 1994 at which point plastic bottles/pouches became the dominant packaging container (see Figure 2).

Continued

Figure 2.



Sales of liquid milk by container type (13)

Barriers to Reuse

Throughout the food and drink industry, the introduction of plastic as a packaging material has brought new capabilities. Plastics 'plasticity' has enabled milk bottles to be shaped with a handle making it easier to carry and pour (14). The ability to create bottles of a larger size coupled with developments in domestic refrigeration has allowed milk to be sold in bulk and stored for longer in the home. Purchasing milk in higher volumes reflects a wider social trend of bulk shopping instead of daily grocery shopping as the supermarket superseded the milkman. In 2016, almost two-thirds of milk purchases were in a four pint or two-litre container, whilst only 4.9% were bought in the traditional doorstep pint size (15).

A report on refillable glass container systems reported that "the traditional one pint refillable glass milk bottle [was] not suited for the retail shelves" (16). Indeed, whilst glass was a valued material for packaging products, it also had its critics. Marks and Spencer's Packaging Department offers an insight of the emergence of plastics (specifically PET) and its relationship with glass. Compared to plastics, glass packaging contributed considerably to the overall weight of the product, thus reducing the overall potential spend in store (17). Glass was also prone to breakage and doorstep milk bottles were susceptible to slipping through the fingers (18). Plastic on the other hand, if dropped, would not smash or cause damage in the home.

The return system of glass bottles was also a victim of social and cultural changes. With the increase of women in the workplace, milk was often left out on the front porch all day if delivered too late. Between 1993 and 1996, liquid milk consumption fell by 14%, which Ward attributes to traditional products such as milky drinks, rice pudding and custard being replaced by pre-prepared convenience foods (19). Dietary issues related to animal fats also changed the public perception of milk (20) resulting in the more diverse milk market that we see today.

During a sitting on the 'Milk-based Drinks Regulations' (1983), doorstep delivery was highlighted as being paramount for the elderly, the mother and her young children and those without easy access to supermarkets. Whilst doorstep delivery was a highly effective means of selling goods then, when car ownership and public transport infrastructure were limited, people now generally have better access to supermarkets.

Market factors, particularly the deregulation of the Milk Marketing Board (MMB) in 1994, accelerated the demise of 'the daily pinta' (21). The MMB's main activity was the collection and sale of milk in England and Wales (22). The 1980s and 1990s were a time of radical change within the milk market with the Conservative Government's privatisation and the Board's incompatibility with the EU regime. During this period, large producers sought to sell to the supermarket groups directly, avoiding the scheme entirely (23). With its deregulation in 1994, its successor 'Milk Marque', a voluntary cooperative, controlled 65% of the milk in England and Wales (24). Criticised as an unregulated farmer-owned monopoly (25), Andrew Dare, chief executive of Milk Marque argued that the non-profit-making co-operative provided a vital service in striving to pay dairy farmers a fair return (26). In the summer of 1995 a pint of supermarket milk sold at 28p, whilst a four-pint plastic bottle cost only 22p a pint. In comparison, doorstep delivery milk sold for between 36p and 41p per pint (27). Referring to this disparity, Dixon (28) highlights that supermarkets were able to reduce the price of milk for the consumer by removing the cost of the delivery service.

Leading dairies reacted to and arguably accelerated the transition of milk sold in plastic bottles in supermarkets. For example, Northern Foods restructured their business reducing their glass-bottling capacity and contracting the doorstep market whilst continuing to invest in the supermarket sector (29). Developments in the milk industry supported the centralisation of bottling and the operation of scale economies. Major capital investment focused on product and packaging innovation in developing close relationships with major multiple retailers (30). Refrigerated storage and transport improvement throughout the supply chain increased the shelf life of milk (31) and enabled plastic bottles to be rolled onto lorries, into supermarkets and then directly into supermarket aisles (32).

Enablers of Reuse

Today, the majority of milk is sold in plastic bottles from the supermarket, however bottled milk in glass has retained or acquired positive associations in terms of provenance, citizenship, sustainability and convenience.

Today's doorstep Milk Deliverers argue that their milk is fresher, superior in taste and has provenance compared to supermarket milk (33). Tracing this back, the doorstep pint has regularly been associated with a rural idyll, coming from local farms via a regional diary whilst milk from supermarkets is associated with a larger nationalised distribution scale (34). The glass milk bottle then communicates traceability and some consumers are happy to pay more in support of British farmers (35). Vaughan et al. also highlight that consumers continue with the milkman service as a way of keeping him employed and to provide social functions such as keeping an eye on the elderly (36).

The glass milk bottle is generally regarded as one of the most environmentally friendly forms of packaging, which became ever more important with the emergence of its plastic competitor. Many environmental groups saw the transition from reusable glass to plastic as a retrograde step (37). Most recently, the 'Blue Planet Effect' has contributed to customers moving back to the glass bottle (39). Yet in 2014, Dairy Crest argued (in the midst of announcing plans to phase out the glass milk bottle) that plastic was now more environmentally friendly than glass (40). The UK Dairy Roadmap states that 85% of HDPE milk containers are currently recycled, with a recycled content used in HDPE milk bottles peaking at 31% in 2014 (41).

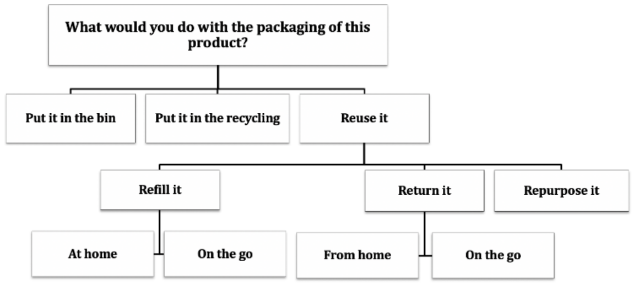
In order to address confusion amongst the public on this issue, a short study was performed by the University of Sheffield on the behalf of Our Cow Molly, a small dairy farm on the outskirts of the city. HDPE vs returnable glass bottles were compared for doorstep delivery. For a delivery radius of 7km, the glass bottles were found to result in lower CO_2 emissions than HDPE, provided that glass bottles were reused at least 12 times. It must be stressed that this result is case-specific and that results will vary with a number of factors, such as transport distance and type, as well as the number of times a glass bottle is returned and reused (42).

Müller, who purchased Milk and More from Dairy Crest in 2015 and decided to retain glass bottle delivery, argued that as a consequence of online shopping having food delivered to the home has led to people getting used to a certain level of convenience (43). In 2019, 30% of UK households had purchased food or groceries for home delivery that year (44). The Terracycle-owned 'Loop' initiative is currently planning the UK trial of a new online doorstep grocery delivery service. Utilising returnable packaging, the scheme has consequently been named the 'milkman reimagined' (45). With such developments, milk in returnable bottles may once again become a convenient product to deliver to the home.

2. What people are willing to reuse, when, and what factors influence this decision?

If reuse is to become the norm, then we need to understand what people are willing to reuse, how, and why. This section covers 3 related studies.

Figure 3.



Overview of the product choice task in Study 1.

Study 1: What are people willing to reuse, how, and why?

Study 1 explored what people are willing to reuse by presenting participants with images of different products and asking them to decide whether or not they would be willing to use the packaging again and, if so, how (e.g. would they prefer to refill it themselves or return it to the manufacturer to be refilled for someone else?). 90 products were taken from online shopping websites; 54% of the products were food or drink (e.g. food condiments, raw meat, soft drinks), 24% were homecare products (e.g. cleaning products, washing detergents), and 21% were personal care products (e.g. deodorants, facewash, toothpaste). Participants were shown a selection of 30 products in a randomised order and asked whether they would: (i) put the packaging in the bin, (ii) put the packaging in the recycling, or (iii) reuse the packaging if they had the opportunity (see Figure 1 for an overview of the task). Participants who indicated that they would be willing to reuse the packaging were then asked how they would be willing to reuse the packaging (i.e. would they rather refill, return, or repurpose the packaging), and which model of reuse they would prefer (i.e. refill or return from home vs. refill or return on-the-go). Participants were then asked to specify why they had selected that option for that product in order to understand people's decisions with respect to reuse.

The study was completed online by 276 adults currently living in the UK. Across all of the products, recycling the packaging was the most commonly selected option (53%), followed by putting the packaging in the bin (34%), and then reusing the packaging (13%). Refilling and repurposing the packaging were the most commonly selected options for products that participants were willing to reuse (6% for refilling and repurposing, compared to 1% for returning the packaging). To explore which types of packaging people were willing to reuse, the data was analysed to categorise products according to what participants would be willing to do with the packaging of that product. This revealed 13 products in the 'reuse' cluster, including biscuits in a metal tin, milk in a glass bottle, coffee in a glass jar, cleaning sprays and hand wash in plastic bottles. Subsequent analyses will explore which features of the product and/or packaging influence whether or not people are willing to reuse the packaging. To do this, we have coded the products according to a number of different physical characteristics and attributes (e.g. material for the packaging, nature of the contents, shelf life).

Study 2: At what point does reuse become unacceptable?

Implementing a successful model of reuse relies on people being willing to reuse packaging and containers multiple times. However, containers that are frequently filled and used will usually become worn and discoloured over time. Study 2 therefore investigated whether and how changes in the appearance of a container influences people's subsequent willingness to use the container.

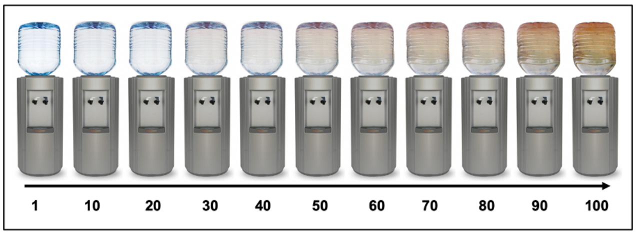
A new task was developed in order to assess the point at which people deem a container unacceptable for reuse. A total of 100 images of water coolers were created that varied from clean to dirty in order to mimic changes in appearance over time (see Figure 1 for examples of the stimuli). Participants were asked to imagine themselves in various scenarios (e.g. attending an interview) and to indicate whether or not they would be willing to have a drink of water from the image of the water cooler presented on the screen (responding either 'Yes' or 'No'). The task determined participants' 50% threshold; that is, the version of the water cooler for which participants responded yes and no equally often, thus reflecting the point at which participants' decisions changed (i.e. from 'no' they would not be willing to drink from the water cooler to 'yes' they would be willing to drink from the water cooler).

The second aim of Study 2 was to explore whether participant demographics (e.g. age, gender, ethnicity) and individual differences (e.g. feelings of disgust, concerns about the transmission of infectious diseases, pro-environmental attitudes and behaviours) were associated with the point at which people deem reuse unacceptable.

186 participants completed the judgment task followed by a questionnaire. Participants' 50% thresholds ranged from 16 to 70 (mean = 40), indicating that there was substantial variation in the point at which participants deemed the water cooler unacceptable for use. We also devised two versions of the task; one version in which a dirty version of a water cooler was shown first (i.e. water cooler version 90) and one in which a clean version of a water cooler was shown first (i.e. water cooler version 10). Participants' thresholds were significantly lower when they were presented with clean versions of the water cooler first (mean = 34) compared to when participants saw dirty versions of the water cooler first (mean = 45).

To provide evidence pertaining to the validity of this task, we also asked participants to rate how thirsty they were and how long it had been since they last had a drink prior to completing the judgement task. As would be expected, there was a

Figure 4.



Example stimuli from the judgement task in study 2

significant, positive relationship between how thirsty participants were and their 50% threshold, and a positive relationship between the time since participants last had a drink and their 50% threshold. Finally, we explored whether the point at which participants found reuse unacceptable was associated with demographics and individual differences. Participants age, gender, ethnicity, or country of origin was not associated with their 50% thresholds. Furthermore, we did not find significant relationships between feelings of disgust, perceived vulnerability to disease, or pro-environmental attitudes and behaviours, suggesting that variations in people's willingness to reuse cannot be explained by these factors.

Study 3: How does the ownership and appearance of a container influence people's willingness to reuse?

Study 3 sought to provide an additional test of the hypothesis that the appearance of a container (e.g. clean vs. dirty) would influence people's willingness to reuse it and also examine an additional factor that may influence reuse - specifically, who owns (or previously owned) the packaging (e.g. owned by oneself vs. a known other vs. a stranger) - termed its "social history".

A total of 238 participants were presented with images of four containers; (i) a reusable coffee cup, (ii) a plastic water bottle, (iii) a plastic takeaway container, and (iv) a reusable straw. The image of the container that participants saw was either clean or dirty and was accompanied by text describing the ownership of the container. Participants were either told that: (i) this was their own container, (ii) they had borrowed this container from a friend, or (iii) this container was given to them by a stranger. Participants were then asked to rate how willing they would be to use the container on a 5-point scale ranging from "completely unwilling" to "completely willing".

First we explored whether people's willingness to reuse a container differed according to the container in question, independent of the appearance or ownership of the container.

Participants were significantly more willing to reuse the coffee cup in comparison to the other products, and participants were significantly less willing to reuse the straw in comparison to the other containers. Next, we explored how the appearance and ownership of the product influenced people's willingness to use the product. Across all of the products, participants were more willing to use the product when it was clean compared to when it was dirty, and when it was their own container compared to when the container belonged to a stranger.

Willingness to reuse two of the containers (the takeaway container and the water bottle), was influenced by an interaction between the ownership of the container and appearance. For example, there was no difference in willingness to use a dirty takeaway container regardless of who owned it. However, if the container was clean, then people were equally willing to reuse a container that they or a known other owner, but were less willing to use the container if it was owned by a stranger. Together, these findings suggest that appearance may interact with social history to determine whether people are willing to reuse.

3. Life Cycle comparison of single-use and reuse in takeaway packaging

The aim of this section of work was to assess the potential environmental impact of replacing single-use plastic with alternatives. Similar analysis has previously been conducted but without considering a return model of reuse (46). To do this, a range of packaging options for a small takeaway meal, of the type that might be purchased for lunch, were compared.

Takeaway packaging

Common types of takeaway food packaging (foodservice packaging) are the expanded polystyrene (EPS) "clamshell" tray, the aluminium foil tray, often used with a cardboard lid, and the plastic (polypropylene) microwave tray. These are all single-use items, which are favoured by takeaways as they are cheap and offer reasonable physical and thermal protection for the food they contain.

However, in recent years, consumer awareness of environmental issues and the potential negative impacts of plastic packaging has led to the development of alternative packaging for takeaways. One alternative packaging option is the Bagasse clamshell, which is marketed as a direct alternative to the EPS clamshell. Whilst the item is still ultimately single-use, Bagasse is a waste product from the refinement of sugarcane, so is perceived as having a lower environmental impact than traditional fossil-based plastic products.

Instead of the replacement of single-use plastic with alternative single-use options, another alternative is the use of reusable containers. Instead of using and disposing of a single-use item, reuse models involve a durable container which is used, washed then reused.

There are two main types of reuse: The consumer owned Refill model, and the business-owned Return model. In the former case, the customer washes and stores the product between uses, whereas in the latter case the washing and storage are undertaken by the takeaway, or in some cases by a third party, allowing it to be used at multiple takeaways.

The most common form of packaging for customer-owned refill is a plastic Tupperware® or similar box. These boxes are commonly made of polypropylene and are generally more robust than the single-use items. Metal boxes are also common, in some cases (e.g. the EcoBox system in Luxembourg) engineering polymers such as PBT have been used, and in other cases a Tupperware type box has been adopted.

Cases

A total of 8 cases were developed in order to represent various options for single-use, eco single-use, refill, and return. In each category, the most commonly-used packaging was selected. In some categories multiple types of packaging were used in order to represent a range of material options.

Single-use:

1. Expanded polystyrene tray with attached lid
2. Polypropylene Takeaway container with lid
3. Aluminium foil Takeaway tray with cardboard lid
4. Bagasse tray with attached lid

Return (business owned):

1. Polybutylene terephthalate (PBT) bowl with Polyethylene lid
2. Tupperware-style Polypropylene box with lid

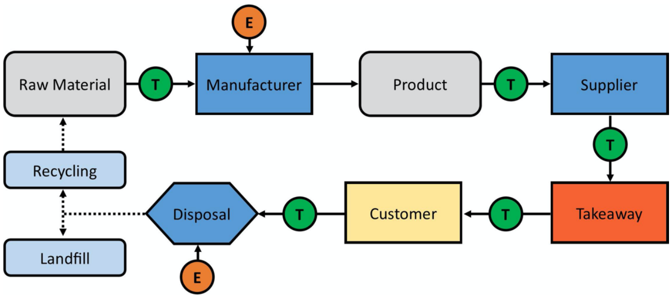
Refill (customer owned):

1. Steel tin with lid
2. Tupperware-style Polypropylene box with lid

Single-use

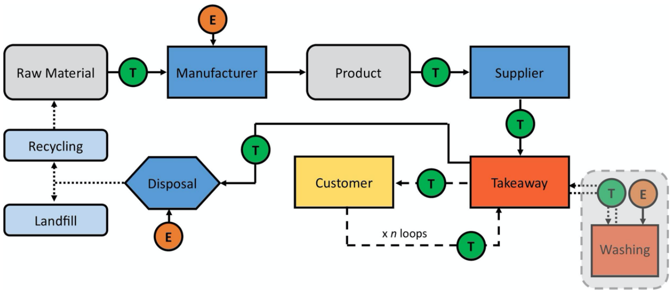
Across all cases, the process of manufacturing and distributing each container is fundamentally the same: Raw materials are transported, processed and manufactured into the product, then transported to a supplier.

Figure 5.



*Flow diagram for **single-use** case showing key transport ('T') and energy ('E') inputs*

Figure 6.



*Flow diagram for **return reuse** case showing key transport ('T') and energy ('E') inputs*

In the single-use case (Figure 5), the containers are purchased by a takeaway and transported from the supplier. At the takeaway, containers are filled then sold to the customer. After use, the containers are disposed of to either landfill or recycling depending on the material.

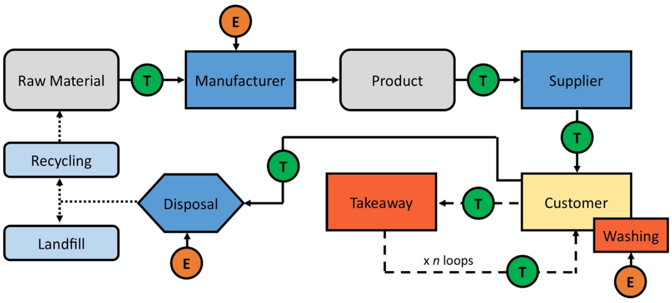
Return

In the return case (Figure 6), the process from raw materials to supplier is the same, but differs thereafter. The container is purchased from a supplier by the takeaway, then enters a loop, where it is filled then sold to the customer, then returned to the takeaway for washing and storage.It is assumed that the returnable takeaway containers are effectively reused by a single takeaway, rather than being used at multiple takeaways as part of a larger scheme. If the return container is owned and washed by a third party as discussed previously, an additional loop is added.

Refill

The refill case (Figure 7) is very similar to the original return case, with the takeaway and customer reversed. The refillable container is owned by the customer, who is now responsible for washing and storage.

Figure 7.



*Flow diagram for **refill reuse** case showing key transport ('T') and energy ('E') inputs*

Methodology & Assumptions

Functional unit: The basic case for comparison is the packaging of 300g of takeaway food from a takeaway restaurant to a nearby place where it is consumed by the customer. Transport between the takeaway and the consumer location is assumed to be on foot, so has no environmental impacts attached to it. In order to compare reuse and single-use cases, we calculated life cycle impacts for all cases.

Manufacture, transport, and end of life: For each material, the most appropriate standard manufacturing method was applied. Much of the data required was taken from the well-respected Ecoinvent3 database.

All single-use containers (EPS Clamshell, Polypropylene box and Aluminium tray) have been assumed to be manufactured in China, then transported by lorry to Shanghai port, where they are shipped by sea to Felixstowe port, then transported to a large catering supplies company in Bristol. From here they are transported to the takeaway.

The most complex route was the Bagasse clamshell, which is made in the USA, from raw material from Brazil. PBT is manufactured from raw materials to completed containers in Germany, then shipped to the UK. Steel boxes and PP Tupperware-style boxes in all cases were manufactured in China.

End-of-life treatment was again based on the most likely disposal method for each container type in a typical UK city. Expanded polystyrene, Polypropylene, PBT and Bagasse are commonly not collected for municipal recycling in the UK, so it was assumed that these containers were sent to landfill after use. Aluminium foil trays are assumed to be recycled by municipal collection, but their cardboard lids are assumed to be disposed of in landfill, since these are coated and are likely to be contaminated. Steel is fully recyclable, and is assumed to be collected by municipal collection and recycled.

Results:

Results were compared across 18 key impact categories for all eight cases, as well as additional cases for the steel box with extended lifetime (100 uses and 200 uses). The best-performing containers were the Tupperware-style and PBT boxes in the return scenario. Return systems performed better than refill systems due to the lower energy and water use of commercial relative to domestic dishwashing (even including the assumption in a return system the container was transported 1km for washing).

The worst performing containers were generally the single-use containers, particularly the PP microwave container and the Aluminium foil tray with lid. The EPS Clamshell performed relatively badly, but was helped by its low weight, meaning that per container transport emissions were lower compared

Figure 8.

Packaging format	Use type	Headlines from results
EPS Clamshell	Single	Best performing single-use item, but non-recyclable so potential litter impacts.
Microwave	Single	Overall worst performer, to be avoided. High fossil resource use, high ozone formation.
Alu Foil	Single	Negative environmental impacts, high CO_2 emissions, but tray is recyclable.
Bagasse Clamshell	Single	Raw material is a waste product. Best option where reuse is impossible and litter is a concern.
PBT Luxemburg	Return	Overall best performer. Return system offers improved washing efficiency over refill. 1
Tupperware	Return	Second best overall. Good overall, but important to recycle at end of life. 2
Steel tin	Refill	High mass causes transport-related impacts, but can have a long life and fully recyclable. Good option 3
Tupperware	Refill	Where return is not possible, refill is still a very good option.

Highlights of LCA results comparing single-use, refillable and returnable takeaway containers

to the PP and Aluminium. The Bagasse Clamshell performed well in some categories (such as fossil resource use), but badly in others (such as Freshwater and Marine ecotoxicity).

Highlights of the results for each container and use type are shown in Figure 8.

Single-use packaging of the types considered here cause significant environmental impacts in all impact categories. Three key impact categories are often considered: Global warming, land use, and water use. Considering only the single-use cases, the PP container performs worst in land use and global warming terms, whilst the EPS Clamshell does so in water terms.

Considering the reuse options across the same three categories, in general, all reuse cases have much lower impact than single-use cases. Due to its weight, the steel refill container does not become a viable option until its lifetime reaches 100 uses, and even then is outperformed by the Tupperware-style and PBT boxes in many categories. There are however waste disposal issues to be considered in the latter cases, since even if recycled these polymer products will eventually require disposal. These issues are perhaps less prominent when steel is used, due to the inherent recyclability of the material.

Conclusions:

- Once a returnable PBT container has been used five times, CO2 emissions per takeaway are lower than any single-use option, and continue to fall over its lifetime.
- Reusable containers perform better than single-use containers in every measure of life cycle environmental impact.
- Business-owned return containers perform better slightly than consumer-owned refill containers, since the business is able to offer more efficient cleaning.
- Steel containers last longer, but are heavy so have greater environmental impact. Durable plastic appears to be the least environmentally damaging material choice.

4. Polymer Technology

From the life cycle analysis, it is clear that reusable packaging must be durable enough to withstand tens to hundreds of reuse cycles to be competitive in many of the environmental impacts. However, it is also clear from the behavioural studies that there will be a point at which a reusable container will no longer be accepted by the public (e.g. it is too worn or discoloured) and that this is influenced by who owns the container. Consequently, the choice of material(s) for reusable packaging must consider performance criteria including:

i. physical and chemical durability e.g. can the container withstand the return and washing process without loss of its containment properties?

ii. absorption and leaching of contaminants e.g. do the containers get stained by the food or product contained?

iii. leaching of additives e.g. are plasticisers lost during use that may either contaminate food or degrade the physical properties of the container?

iv. containment properties e.g. does the material provide an adequate gas barrier to prevent entrance of oxygen that would spoil the product?

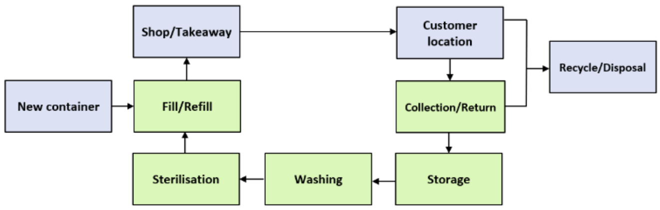
Additionally, to maximise circularity in the system, any containers should be designed with recycling in mind e.g. mono-materials or easily separable, minimal additives etc. As iii. and iv. are important considerations for single-use packaging, only i. and ii. will be considered here.

The cycle of reuse

During its lifetime, a reusable container will be exposed to a range of physical and chemical conditions. Using plastic bottles as an example (Figure 9):

1. After the initial fill, the bottle will be delivered to the point of sale, shop or delivery depot.
2. The bottle is then transported to the customer's location (e.g. home, office) by the customer or delivery service (storage/transport).
3. The empty bottle then collected (e.g. roadside collection) or returned by either the customer or the delivery service (transport).
4. The empty bottles will be stored either locally or centrally (storage).
5. The empty bottles will be washed and sterilised (washing).
6. The bottles are refilled and delivered to the point of sale (transport).

Figure 9.



An example cycle of reuse for a food container.

This cycle of reuse puts a bottle through a range of physical and chemical stresses during its lifetime. Transport puts the bottle through a range of physical stresses, e.g. abrasion and impact leading to a reduction in failure strength of the bottle, as well as compromising the appearance. Storage can expose the bottle to a range of weathering processes such as exposure to a range of temperatures, water, and UV light, that can chemically alter the materials affecting both mechanical performance and appearance. The washing and sterilising process must be rigorous enough to prevent cross-contamination between fills bringing an additional burden of physical and chemical stress. There is also the possibility of contamination through misuse (e.g. using the bottle as a container for a non-foodstuff) or malice (e.g. deliberate contamination before return) that must also be prevented.

Materials Selection Considerations

As highlighted in the previous section, the bulk of consumer packaging and food containers are currently made with commodity polymers, typically polyolefins including polyethylene (PE) and polypropylene (PP), polyethylene terephthalate (PET) and polystyrene (PS). Due to their wide acceptance within the industry and low cost it could be expected that these will remain as the main plastics in food packaging. However, to meet the required function more expensive engineering polymers such as polyamides (e.g. nylon-6), polycarbonate (PC), polyethylene naphthalate (PEN), polybutylene terephthalate (PBT) and emerging polymers e.g. polyethylene furanoate (PEF) should also be considered.

Physical and chemical durability

Jetten and de Kruijf have studied the effects of repeated wash cycles on PET and PC bottles, and PP vending cups. The washing process was not fully described but was performed at a commercial facility for washing catering articles so can be considered moderately representative. For PET and PC bottles, the gas and vapour permeability of the bottles was unaffected after 15 washes, indicating good tolerance to the washing process (47). The effect of environmental weathering on commodity plastics such as high-density polyethylene (HDPE) has been widely studied (48) and demonstrates that the physical properties of HDPE are significantly affected by intense UV radiation leading to both random chain scission and photo-oxidation of the polymer chains. These temperature dependent processes result in embrittlement and early failure but can be mitigated by additives, such as UV absorbers and radical quenchers (49).

Absorption and leaching of contaminants

There is a significant risk posed by the transfer of contaminants between fills, particularly food allergens. To avoid segregation of packaging during use and the refill loop, methods for both decontaminating and evaluating contamination are required.

Jetten and de Kruijf determined the migration of plastic-related contaminants from PET and PC bottles after 1 and 15 washes using a range of simulant fills (3% acetic acid, 50% and 90% ethanol, olive oil, and iso-octane). Their results indicated little, or no, difference in the amount of leaching after repeated washing (50). Jetten et al. studied the persistence of simulated fills in virgin bottles and washed bottles (15 cycles) after a washing cycle. Fills included chemical contaminants (e.g. solvents and cleaning products), flavour carry-over (e.g. fruit syrups), and other contaminants (e.g. urine). Both chemical and flavour carry-over contamination was evident in bottles later refilled with water and was not dependent on the history of the bottle, i.e. one contaminant fill was sufficient. This highlights the importance of adequate washing and testing for contaminants to prevent tainted products upon refill (51) and points towards the need for product segregation in reusable packaging.

Summary

Overall the literature on the reuse of plastic packaging is limited and does not consider the reuse cycle as a whole. In order to understand whether a plastic package could be suitable for a reuse scheme more appropriate experiments need to be performed. These would critically compare the performance of different plastics via test methods which truly replicate the conditions which would be experienced in reuse processes. It is also important to develop testing methodologies that consider the effects of reuse on the quality of the contained product and ways to prevent these contaminants entering the refill cycle.

Discussion

The research conducted in all four of the workstreams above has considered barriers and facilitators to making packaging reuse systems mainstream. The grey literature review in 1 considered the decline and recent championing of a previously successful model, doorstep milk delivery in glass bottles. The decline cannot be attributed to a single factor but to a combination of technological, economic and social change. These include the development of new materials (lightweight, more robust), social changes (in women working outside the home, the rise of private car ownership and supermarket shopping) and economic factors (supermarket price competition, capital investment in plastic bottle systems and the economies of scale of a centralised milk industry). The current championing of doorstep milk in returnable bottles can be attributed to a similar range of factors (predominantly social and technological) including: provenance, citizenship, sustainability and convenience. Whether these reasons alone will enable a mainstream return is unknown, but unlikely without additional facilitators.

The work in Part 2 investigated the product packaging that consumers were most likely to reuse, covering a range of products over food, personal care and household care. Interestingly the products identified were for where there is already a precedence set; milk and carbonated drinks have been supplied using packaging return systems within living memory, coffee refill packs have been popular for a number of years, and it is likely that most people have a repurposed biscuit or confectionary tin somewhere in their home. A method was also devised in order to assess acceptance of a container that was worn or discoloured from multiple uses. A final study highlighted the importance of the past history of a container in relation to the individual's willingness to reuse it.

The life cycle assessment performed in 3 on single-use versus both returnable (company-owned) and refillable (consumer-owned) reusable takeaway containers showed that in the given scenario, and providing they are used enough times, both out-perform single-use takeaway packaging in every measure of life cycle environmental impact. Of course, the reusable plastic containers need to be both physically and visually up to the job (ref. work from 4 and 2), the number of possible rotations still to be established. The practical work originally planned for 4 examining the durability of a variety of standard and food-grade engineering plastics had to be halted due to the outbreak of COVID-19. However, the LCA results show that a container made from the engineering plastic PBT requires only 5 rotations before outperforming any single-use item in terms of carbon dioxide emissions. In fact, durable plastic appears to be the least environmentally damaging material choice, even when compared with steel.

The polymer materials literature relating to packaging reuse reviewed in 4 identified that research into this area is limited and more experimental work needs to be performed on the behaviour of the materials over many duty cycles. The materials selection criteria for single-use packages (cost, light-weight, aesthetics) are clearly not appropriate for reusable containers so it is important that more expensive, but higher performing plastics are considered for the more demanding duty cycle whilst also considering a mechanism for recycling the container once it is too damaged to use again. We know from our stakeholder workshops that contamination is a concern and this will form an important part of future lab work.

Whilst it was the original intention of this work to concentrate on returnable packaging systems, it has become evident through stakeholder engagement that refill models are being considered seriously by both retailers and brands in order to achieve their UK Plastics Pact commitments. This makes sense - refill systems are simpler for an operator to introduce as they can slot into existing supply chain models relatively easily – return systems require considerable investment – e.g. reverse logistics and washing facilities for a brand or retailer of , or simply a dishwasher and the space required for it for a takeaway - a significant commitment for a small business owner.

Conclusions

'What is required in order to make reusable plastic packaging systems mainstream?'

We have shown that there are many factors at play for the success of a reusable packaging system for fast moving consumer goodsfast moving consumer goods, convenience being just one. In previous literature (52), it has been shown that the length of the supply chain is a factor in determining whether a single-use or reusable packaging system is the most effective from an environmental point of view, and this is supported by factors described in the milk case study. Consumer acceptance is key and our willingness work shows that customers will need to be led by brands and retailers in order to start using new systems at scale. A method by which to test a consumer's acceptance of worn or stained packaging has been developed and it has been established that the history and history of a container affects people's . For the scenario of a single takeaway meal we have shown that, providing the requirements of consumer acceptance and material durability are met, returnable plastic appears to be the least environmentally damaging choice. We have identified that more experimental work needs to be performed so the behaviour of plastics for reusable packaging is known.

It is clear that both returnable and refillable packaging systems can help solve the Plastics Problem. Future work will build on the work above and look at developing a methodology to determine which reuse model is best for any given scenario.

Next Stage

We intend to continue our interdisciplinary approach to working, with five work packages - Change, Willingness, Lifecycle, Technology and now Language, with frequent communication between these packages and key stakeholders, under the name of 'Many Happy Returns'.

Conflicts of interest

There are no conflicts to declare.

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Plastics: Redefining Single-Use investigators and stakeholders.

Grantham Centre Colleagues – Stefanie Tille, Deborah Beck, Jana Kalalova and Eva Vichova.

Notes and references

*Milkman, woman, person or deliverer. Milkman is used here because of the historical context.

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Facilitating interdisciplinary and systemic solutions: the SYSFOCUS approach to the plastics challenge

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When tackling complex issues such as the global proliferation of waste that results from widespread plastics applications, looking for solutions from the partial perspectives of materials science, manufacturing engineering , or the social sciences is not sufficient. Instead, such issues require a socio-material perspective using systemic and interdisciplinary thinking and practice. In this paper we outline the SYSFOCUS methodology which facilitates the development of socio-material solutions for wicked and complex issues such as the plastics challenge, and illustrate this with intermediate results from the RE3 project undertaken at The University of Manchester. We have found initial support for the added value of this facilitation process, leading participants to substantially change their projects, and identify the viability of using SYSFOCUS in other subject areas.

Introduction

The use of plastics is widespread in societies worldwide; this rather diverse category of materials (perhaps better labelled as – fossil fuel-based – polymers, but we will follow common parlance) has become an established source material for products in all industrial sectors and systems of provision. This is the result of a remarkable process of diffusion which started in the 1950s. The diffusion of plastics has been accompanied by concerns (fluctuating in intensity) over negative side effects, both in terms of health of production workers and the range of environmental impacts they generate. In the past few years, public concern has intensified considerably, to which national governments have responded with a range of policy interventions. The PRIF initiative, through which the reported research is funded, is an example of such an intervention.

The combination of engrained use of plastics throughout society and persistent concern about the environmental impacts of this category of materials constitutes a complex and wicked issue as defined by Head (2008): it combines *complexity* of interrelated social, material and ecological dynamics, *uncertainty* over risks and consequences of solutions, and *divergence* of positions over what are legitimate courses of actions to address the issue. To accommodate these characteristics of what is sometimes referred to as "the plastics challenge", The University of Manchester's PRIF funded *RE3: Rethinking Resources and Recycling* project adopts a systemic and socio-material perspective. *Socio-materiality* is the perspective that recognizes that issues that are associated with a material (in our case plastics) emerge from the interplay of material characteristics and social practices of production and consumption through which these materials are created, transformed, used and disposed of (Orlikowski, 2007). It is not the materials in themselves that pose a problem; the materials become an issue through how they are handled in practices of production and consumption. A *systemic perspective* is required because plastic applications occur in larger systems, such as plastic packaging in the food system, medical appliances in the system of health care, and synthetic fibers in the system of clothing. Changing the material involves the technological infrastructure and practices of actors in these wider systems. Therefore, partners from industry, businesses, city councils, public services, and utilities are crucial to provide insights into the functioning of these systems of provision and should be part of developing solutions as collectively they can provide the necessary understanding on how these systems function. In developing solutions, reflection is needed that any socio-material solution, when generated and applied in one part of the system, should not create *unintended consequences* in another part of the system in the present or the future.

This article presents the steps in the SYSFOCUS process which brings together these actors to facilitate the development of sustainable and impactful socio-material solutions, and illustrates these with insights from applying SYSFOCUS in the RE3 project. In the next sections we will concisely outline the facilitation process. Based on our still developing insight, we conclude with calls for more responsive research on sustainability issues to embrace systemic and interdisciplinary methodologies of knowledge co-production.

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The SYSFOCUS toolbox: Generating systemic Insights for wicked and complex issues

SYSFOCUS aims to facilitate a process of responsible innovation where academics collaborate with industry partners and societal stakeholders to address the wicked and complex issues that currently exist in a chosen system of provision. Both industry and societal stakeholders need to be involved given the diversity that such issues display. SYSFOCUS outlines a two stage process: The first stage aims at developing research projects for potential system interventions by creating a shared understanding of the system among participants with diverse backgrounds. The second stage then aims to responsively and responsibly conduct these research projects and collaboratively develop plans for implementation and impact. Although a majority of the actual research and development work is done in stage two, the foundation for sustained and productive collaboration is created in stage one. Timewise, the second stage should only be around twice as long as the first stage. The two stages, which are outlined in the following, extends and combines proven facilitation techniques; the extensions and the combination of tools is unique for SYSFOCUS.

Stage 1: Understanding Systems and Identifying Issues

The first stage of the process consists of learning histories to help build a shared understanding of systems and how they become a certain way; of change point workshops to discuss and discover how both social and material elements of systems may be altered to enhance sustainability; and lastly a sandpit workshop to identify meaningful projects groups intending to work on them.

Learning Histories – Combining organizational development techniques with event sequence analysis (Spekkink, 2016; Boons & Spekkink, 2016) and other process-based research methodologies, learning histories in SYSFOCUS are a means to understand, analyse, and comprehend complex developmental trajectories, such as the emergence of the use of a technology and related impacts. The technique was first developed to facilitate processes of organizational development, and subsequently extended to apply to wider systems. The combination with event graph depiction is a first innovation of the SYSFOCUS approach. Earlier experiences with validating event graphs informed us of the positive effect of using networked visualizations of historical processes as a vehicle for multi-stakeholder work. Combining this with the learning history approach allows us to get a diverse group of participants, each knowledgeable about a part of the system and its history (based on their role and past experience), to collectively reflect on the history of the system.

This approach requires a preparation of a networked timeline, which potentially is highly time consuming. It should be noted that the timeline is not supposed, in this first iteration, to adequately and completely represent the history of the system; it should capture essential events and their connections in such a way that participants can engage with the timeline, and as part of the discussion they extend and correct it. In RE3, the preparation served the additional aim of bringing together post-doc researchers from different disciplines. Led by a social scientist, they collected data from the Internet and academic literature on three systems and coded the data using a coding scheme using the following categories:

- **Contestation**. Actors challenge knowledge claims related to intended or realised actions of other actors.
- **Mass Production Economics**. Supply chain and post-consumer chain organizations develop manufacturing and marketing practices based on considerations of resource costs.
- **Strategic Niche Management**. A new technology, product or service, is being developed and tested in a managed way, usually in a restricted geographical space.
- **Lead Time to Market**. an in principle commercially viable innovation requires extensive testing and assessment to become a legitimate option for production and consumption.
- **Market Dynamics**. Relative prices of alternative inputs, intermediate, end products, or waste streams cause the increased use of a particular product or service.
- **Overriding Value**. Attempts to change an entity (practice, product or service) are prevented by an appeal to values that make questioning the status quo non-legitimate.
- **Rules and Standards**. The development and enforcement of rules and standards that affect a material application.

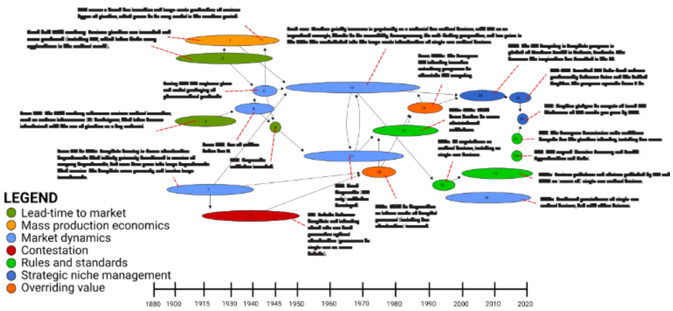

Figure 1: Example of a timeline as developed from the learning histories workshop

Change Point Workshops – The change points workshop is a methodology for group thinking developed by social scientists in order to explore and 'unlock' sustainability-related social or material interventions (Hoolohan et al., 2018). It has been developed for interdisciplinary groups with a shared goal to engage with the complexity of socio-material systems, specifically looking at how everyday practices manifest or influence certain issues and how these might be altered. In these workshops, groups can work around specific topics that emerged from the learning history workshop to identify issues; these include points where change could realistically be brought about, as well as the actors required to achieve that change.

Sandpits – The preceding steps are able to generate shared insights as well as momentum for project partners—academic and non-academic alike—to engage in informal conversations. The increased awareness and insight from the learning histories, and the identified intervention opportunities from the change points workshop, both feed into a sandpit workshop (EPSRC, n.d.). Exploiting that momentum to form collaborative projects, a sandpit workshop helps to make explicit shared interests and goals, and deliver project statements or proposals to be taken forward. Crucially, through the engagement of external stakeholders throughout the process, they are key driver and motivator to firstly formulate and secondly achieve the objectives identified.

Stage 2: Planning and Interrogating Solutions

The second stage of the process engages with the socio-material interventions and the research required to prepare and make them actionable. Facilitating and supporting such process while keeping in mind the previously developed insights, this stage consists of group logic mapping to plan pathways to arrive at actual sustainability impacts; and of causal loop modelling to uncover unintended consequences such as non-sustainable impacts.

Logic Mapping – Logic Maps are often used in project planning and evaluation, and represent a usually linear flow over different components during and after a project lifetime. Common conceptualizations such as those of UKRI include five consecutive steps in a project logic: *Inputs*, *Activities*, *Outputs*, *Outcomes*, and *Impacts*. While the former three are part of the project and are thus directly influenceable, *Outcomes* and *Impacts* tend to occur after the project lifetime and represent immediate or broader changes as a result of a project. Logic Mapping is the process of creating such logic maps, and is often conducted as a group exercise to bring groups together and create a common discussion ground for project evaluation or planning (McLaughlin, Jordan, Newcomer, Hatry, & Wholey, 2015). Similar to the first stage of the project, logic maps (such as the example in Figure 2) can be prepared in advance by means of the project proposals as well as preparatory conversations with the project leads and project participants.

The aim of this workshop is to identify what could be termed 'pathways to impact' by firstly identifying steps to scale or to impact, and secondly by uncovering underlying assumptions and requirements such as contexts, involved actors, funding, government action, or societal attitudes. These are ideally facilitated by an independent chair who probes participants, guides the discussion, and critically interrogates with the participants the emerging or thus far undiscussed elements of the logic map.

The following three elements deserve specific attention in the workshop:

• **Forward-looking Intervention**. Starting from Inputs and Activities and going towards Impacts, it needs to be discussed what specifically constitutes an element; how it will impact the further development of the project; and what other possibly unintended things may be caused by such element which have not yet been mapped.

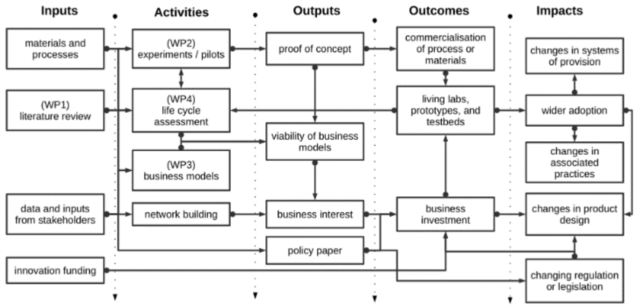

Figure 2: Example of a logic map as developed during the logic mapping workshop.

• **Backward-looking Assumptions**. Starting at Impacts, elements of the project logic need to be critically interrogated to uncovering the assumptions and requirements beyond those already mapped. Assumptions and requirements may include changing social attitudes, continued funding, government intervention or inaction, or specific economic viability.

• **Feedback loops**. Although logic maps tend to be linear in their setup and are thus not entirely suited for thorough systems thinking (Renger, Atkinson, Renger, Renger, & Hart, 2019), they frequently include feedback loops which may for example connect a specific outcome to an adjustment in inputs or activities. While these can not always be mapped, they generally signify iterative research processes such as an interaction between material synthesis processes and life-cycle assessments in order to only follow up on intervention pathways identified as 'sustainable'.

Such systematic approach of discussing a project or intervention logic is useful to expose differences in assumptions about the what the project ought to do, adjust the project to emerging insights, and create a joint understanding of the issues related to implementations. The workshop ends with a discussion of the next steps in the project, specifically regarding how projects need to be altered and what measures need to be taken to ensure the project can generate sustained impact beyond the funding period.

Causal Loop Modelling – System dynamics modelling is a common tool to quantitatively model and analyze but also to qualitatively interrogate and visualize the complexity of specific systems. These models are frequently used as group modelling exercises to enhance participants systems thinking (Luna-Reyes et al., 2006) and whilst not always furthering their insights it makes more explicit the underlying understandings of system dynamics (Vennix, Akkermans, & Rouwette, 1996). Causal loop diagrams are one such system dynamics model, but unlike other conceptualizations they ignore stocks and flows and only focus on the ways in which different elements influence each other in linear or circular ways.

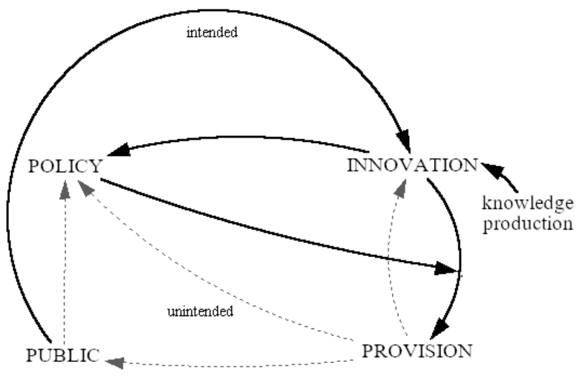

Figure 3: Overview diagram of how the system of provision interacts with public, policy, and innovation

A causal loop group modelling exercise is used to map the system which is leading towards and emerging from an intervention, in order to uncover additional complexities and unintended consequences of the project. Assuming that most unintended consequences and non-sustainable impacts arise from an incomplete understanding as opposed to lack of understanding (which is not always the case), these may actually be uncovered and mitigated or avoided. Just like the previous steps, such workshop needs to be prepared in advance using the insights from all previous project interventions, the facilitator's knowledge about and experience with the project, and additional literature research.

Following the notion of socio-material systems, such causal loop diagram necessarily needs to include (a) systems of provision including manufacturing and end-of-life value chains, and (b) publics as part of a consumption system. Based on the insights from the previous workshops we further suggest to explicitly map (c) policy systems or their inactivity. Finally, accounting reflexively for the specific research project and the broader role of research and product development, (d) innovation and knowledge production systems, and specifically the implementation process of the current research project need to be accounted for. These four parts of the system and some fundamental (albeit not complete) understanding of their intended and unintended interactions is mapped in Figure 3. An elaborate causal loop diagram as used in a workshop can be seen in Figure 4.

Since the purpose of this workshop is to uncover unintended consequences, in preparing and conducting the workshops sources of unintended consequences need to be highlighted explicitly. Bearing in mind that the workshop is meant as an inquisitive and critical intervention as opposed to an exercise to create an actual parametrised model, the exercise should focus on the following elements of uncertainty:

- **Scenario/Ontological Uncertainty**. About the assumptions, limits, and intentions of a model. Including which entities are part of the system and how they interact and change through interactions; what the model boundaries are and whether they are sufficiently decomposable (see Simon, 1962) or whether potential knock-on effects could become relevant; whether all necessary phenomena are included and whether system resolution is properly accounted for (i.e. micro, meso, and macro scale, see Schwaninger & Groesser, 2009); whether all potential impacts and side-effects have been considered, including where they may occur, and whether they could occur at different locations or times.
- **Executive Uncertainty**. About the assumptions underlying an intervention. Including the outcomes of the project and their inevitability or flexibility; whether the necessity for the intervention changes either over time or when looking at different stakeholders; how the system may change as a result of the intervention; how elaborate or limited the understanding of the intervention is; and how the intended model or implementation may differ from the actually implemented intervention.
- **Model/Structural Uncertainty**. Uncertainty about the explicitly taken abstractions to understand and model an existing system. Including uncertainty about the connection, interaction, and influences of elements, and missing sinks and sources. Furthermore, uncertainty about how the system in which the intervention interacts with is different to the current as well as the modelled system, as well as how the trajectory of such intervention might interact with the system (see also Rowe, 1994).

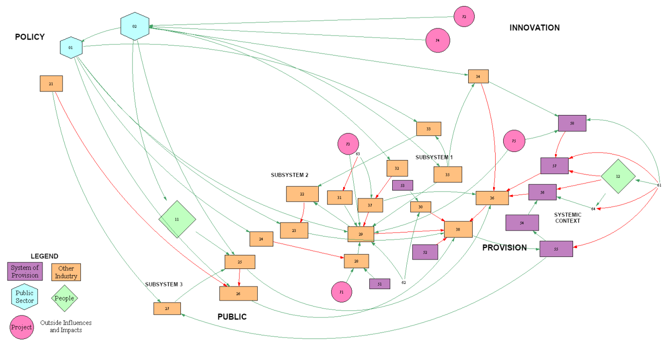

Figure 4: Example of a causal loop diagram mapping the intended intervention in relation to the the different identified systems and subsystems

Application of SYSFOCUS in RE3

In the course of RE3 we have applied the SYSFOCUS methodology. Step 1 was the overarching approach of the first six months of the project; here an interdisciplinary team (with members coming from social sciences and material science) shaped the workshops around three plastics systems: a) single use medical devices, (b) biodegradable (i.e. PLA) food packaging, and (c) synthetic fibers in clothing. For each of the themes we developed an initial event graph, which was updated based on the learning history workshop. This second version then provided a basis for the subsequent workshops. Out of these came project proposals which substantially differed from the projects as proposed in the original RE3 bid. The second step (logic mapping and causal loop modelling of unintended effects) is still ongoing; the workshops provide a platform for open discussion about the systemic consequences of the innovations developed in each project. We will report in detail on the results in subsequent publications.

Conclusions

With its socio-material dynamics, the plastics challenge is like all sustainability challenges not to be solved by linear or reductionist thinking. In this paper, we present SYSFOCUS, a facilitation process to help academics, industry partners and societal stakeholders to engage with and tackle complex and wicked issues within such systems. This process consists of (1) building systemic awareness as a basis for identifying core issues to address, and (2) ensuring that all solutions are impactful, actionable, and without unintended consequences. As such, our work fits with the generic principles of responsible research and innovation (Cuppen, Grift, & Pesch, 2019) and embraces aspects non-linear project management for innovation (e.g. Cisnetto & Barlow, 2020). It can be beneficial to research and innovation activity for all technology readiness levels.

The SYSFOCUS methodology provides a coherent systemic approach to better engage and include stakeholders as well as build a shared understanding amongst interdisciplinary research teams. Even though project participants may have their established understandings of the issues they see in a specific system, our approach is unusual (cf. Ribeiro, Smith, & Millar, 2017) in that it starts with an open-ended building of systemic understanding as well as a collective evaluation of the observed issues. Following from the successful application of our methodology within the RE3 project, we are currently engaged in several research efforts to extend the areas of application and collect more data on the conditions under which this methodology generates useful results

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Conflicts of interest

There are no conflicts to declare.

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Session 2: Fossil & Bio-sourced Plastics

New Building Blocks for Bio-Based Plastics

Esther Ambrose-Dempster,[a] Maria Bawn,[b] Dragana Dobrijevic,[b] Leona Leipold,[a] Tom D. Sheppard,[a] John M. Ward[b] and Helen C. Hailes[a†]

Renewable carbohydrate waste feedstocks have significant potential to enable access to building blocks for the synthesis of new materials and have the added advantage of not competing with land for food production. Here, several approaches to making bio-based polyesters, and waste biomass derived furan building blocks are described, together with promising new biocatalytic approaches for the amination of sugars. These strategies have the additional benefits of creating value from a low-cost abundant feedstocks including waste materials. The research challenges include producing monomers efficiently with suitable properties. Current examples include furanoates (from waste carbohydrates) which are used to synthesise PEF (polyethylene furanoate) which is a bio-based plastic with similar properties to PET (polyethylene terephthalate). The use of new biomass-derived monomers will give great versatility in the polymers formed incorporating hydrophobic and hydrophilic components. Other challenges in moving towards renewable-based polymers will include their performance, scalability, cost, and recyclability. However, our reliance on non-renewable feedstock needs to be tackled now to generate the materials of the future.

Introduction

Petroleum-based polymer demand has increased significantly in recent years. Such polymers, including polyethylene and nylon, have many desirable properties but our exclusive reliance on non-renewable feedstocks for their synthesis is not sustainable. Currently over 90% of organic chemicals are derived from fossil resources and the challenge looking to the future is to source other polymer building blocks. Bio-based feedstocks are at the heart of a bio-based circular economy and provide a major opportunity to develop new monomers for polymer synthesis.

Renewable carbohydrate waste feedstocks have significant potential to enable access to new materials and have the added advantage of not competing with land for food production. To enable this, new technologies are required to provide access to suitable building-blocks. In addition, materials development using bio-based monomers is needed to prepare polymers with the appropriate properties. Furthermore, the recycling of the materials produced needs to be considered. Here we present a perspective on bio-based polymers and new carbohydrate-derived polymer building blocks, with an emphasis on sustainable routes to produce such compounds on a preparative and industrial scale. In particular, the use of biological catalysts will be highlighted and strategies to improve the performance of these.

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Bio-based plastics and polymers

Naturally occurring polymers have been used by humans for millennia. Polymers from plant and animal sources such as cellulose, natural rubber and leather made up of the protein polymer collagen are some examples. More recently new bio-based polymers have been developed to replace petroleum-based plastics. These polymers are derived, fully or partially from natural biomass, such as agricultural crops, lignocellulosic biomass or organic residues and waste. Although referred to as “bio-based”, polymers prepared from these renewable feedstocks are not necessarily biodegradable. Biodegradability studies are necessary to assess biodegradability, compostability and the long-term environmental impact of these materials.[1,2]

Among bio-based polymers, polyesters have seen increased attention and market demand. Poly(lactic acid) (PLA), is currently the most commonly used bio-based polyester, with an estimated global production volume of around 190,000 tons in 2019.[3] PLA (Figure 1), is produced from the polymerisation of lactic acid (LA). Industrially, LA can be produced by chemical synthesis or by fermentation. Bacterial fermentation of renewable biomass with the lactic acid bacteria is the preferred industrial process for LA production allowing access to its optically pure isomers.[4] Further manufacturing processes have been developed for the polymerisation of LA to produce high molecular weight PLA valued in the medical, textile, and packaging industries.[4] Biodegradable and biocompatible PLA has a wide range of applications, from implants, medical devices and drug delivery,[5] to mulch films and packaging.[4]

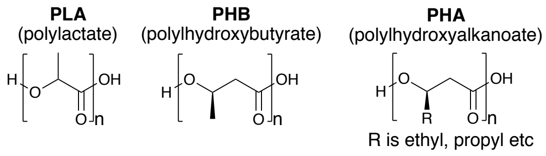


Figure 1. Structures of the polymers PLA, PHB and PLA.

Bio-based polyesters can be also synthesized by bacteria such as poly(hydroxyalkanoate)s (PHAs) (Figure 1), a diverse family of biodegradable polyesters. PHAs are made and accumulated by bacteria in response to external stimuli, as intracellular granules to serve as carbon and energy reservoirs allowing commercial production via fermentation. In bacteria, hydroxyacids with different aliphatic side chains can serve as PHA monomers (Figure 1).[6] Due to this structural diversity of monomers, PHA polymers display a wide range of material properties.[7,8] PHA materials can be rigid with properties comparable to those of polypropylene as well as more flexible materials such as low-density polyethylene.[7] Polyhydroxybutyrate (PHB) is a homopolymer of 3-hydroxybutyrate, produced by many soil bacteria as a storage compound when carbon rich food such as glucose is abundant. PHB and its copolymers such as poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHVB) or poly(3-hydroxybutyrate-co-4-hydroxybutyrate) (PHB4HB), are the main PHAs relevant for practical applications including the production of biodegradable packaging materials and other disposable articles.[9,10] Due to their biocompatibility, they are promising materials for various applications in biomedicine.[4,11,12] Increased production capacities are foreseen for PHAs with an estimated 23,000 tonnes to be made globally for polymer production in 2021.[7]

Biomass-derived monomers for polymer synthesis

Lignocellulose, which comprise lignin, cellulose, and hemicellulose, is the most abundant class of biomass and holds enormous potential as a sustainable alternative platform to fossil fuels. Valorisation of lignocellulosic biomass for polymer production however still remains a challenge with many opportunities.[13] Native carbohydrates are not generally suitable for the production of polymers via industrial processes due to poor thermal stabilities. The incorporation of additives such as plasticisers as well as blending with other polymers, fillers, and fibres can improve material properties. Examples include the application of cellulose in composite materials to replace glass fibre together with thermoplastics or thermosetting polymers,[13,14] as well as thermoplastic starch blends.[15] As a result, degradation of biomass to give monomers for polymerisation into novel plastics is of great interest. In particular the production of building blocks such as succinic acid and furan-based compounds are a key focus.[16,17] Access to important furan examples via platform chemical hydroxymethylfurfural (HMF) using chemical methods and biocatalytic enzymes are described below. Biocatalysis has become established as an important synthetic method due to the mild reaction conditions used, sustainability factors and superb reaction selectivities, and it is increasingly being used at an industrial scale.

Hydroxymethylfurfural (HMF) – a key intermediate

Sugar hexoses such as fructose (e.g. from sucrose) or glucose from cellulose can be chemically dehydrated to form HMF (Figure 2) and similarly pentoses (e.g. arabinose) found in hemicellulose can be chemically converted to furfural. HMF is a platform chemical and an important intermediate for the formation of furan-based polymer building blocks.

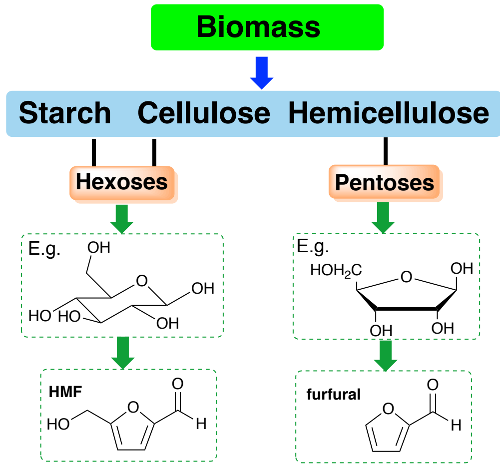


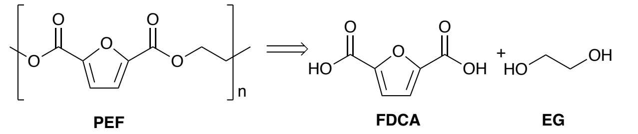
Figure 2. Sources of HMF and furfural from biomass.

Numerous methods have been developed to achieve this cyclisation and dehydration, including heterogeneous catalysts,[18] ionic liquids,[19] and acid catalysts.[20] Renewable carbohydrate waste streams can be used for furan production and include sugar beet pulp in the UK, Northern Europe, North America and many other countries; sugar cane bagasse in Brazil, India and many other countries; wheat straw in the UK, Europe and North America; spent distillers grains from bioethanol manufacture and other agricultural plant wastes that are all sustainable biological sources of the sugars that can be converted into furfurals. The UK has a large sugar beet industry with 8 M tonnes of sugar beet grown annually for sucrose (sugar) used in the food industry. 350 kTonnes of sugar beet pulp (SBP) is left after sucrose extraction and SBP is rich in pectins (38-50%), cellulose (26%) and hemicellulose (24-36%) for accessing high value compounds and other building blocks.[21,22]

HMF as well as furfural has many applications in the preparation of monomers for polymer synthesis. This is typically achieved via oxidation or reduction processes to alcohols and acids or amines, or the addition of an extra carbon as detailed below. They are also used in the preparation of other compounds with applications in the pharmaceutical sector.

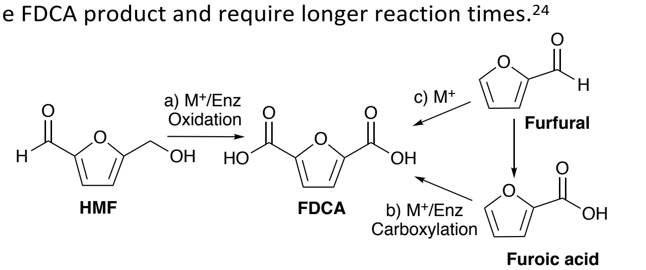
Furan-2,5-dicarboxylic acid (FDCA)

Furan-2,5-dicarboxylic acid (FDCA) is a key building block used in polymer synthesis that is prepared from furfural and HMF. It is a key component of polyethylene furanoate (PEF), a polymer proposed as an alternative to unsustainable petrochemical-derived plastics,[23] specifically polyethylene terephthalate (PET).[24–26] FDCA is combined with ethylene glycol (EG) to make PEF (Scheme 1) and has also been used in synthesising other polyesters,[27] so holds significant potential as a sustainable plastics monomer. Other FDCA based co-polymers include: poly(ethylene furanoate-co-terephthalate) (PEFT); poly(ethylene-co-2,2,4,4-tetramethyl-1,3-cyclobutanediol 2,5-furandicarboxylate) (PETF) and poly(butylene sebacate-*co*-butylene furandicarboxylate) (PBSF),[28] and this activity drives the requirement for production of this monomer.



Scheme 1. PEF polymer structure and its monomer counterparts, FDCA and ethylene glycol (EG).

Synthesis of the key compound FDCA can be achieved chemically or biocatalytically from different starting materials including HMF, furoic acid and furfural (Scheme 2). Popular chemical methods commonly involve the oxidation of HMF, using various metal-based catalysts, including metals associated with ligands (Scheme 2).[27,29–33] The metals used to date include platinum,[34–36] palladium[34] and gold,[30,37] which are relatively expensive and there are sustainability concerns. Metal-free catalysts are therefore being explored but have the disadvantage that they are often less selective for formation of the FDCA product and require longer reaction times.[24]

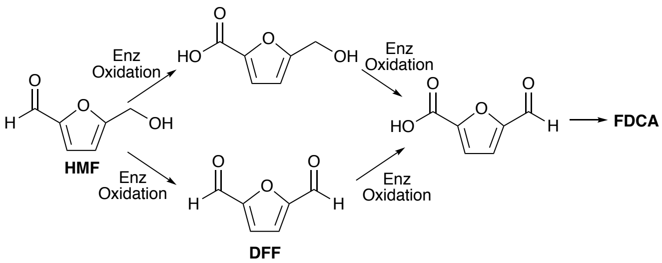


Scheme 2. FDCA synthesis from different starting materials, all of which can be derived from biomass. M+, metal catalyst; Enz, enzyme. a) Conversion of HMF to FDCA.[27,29–33] b) Conversion of furoic acid to FDCA.[38,39] (Both furoic acid to FDCA chemical methods involve oxidation first from furfural.) c) Conversion of furfural to FDCA.[40,41]

Biocatalysis provides a platform to potentially by-pass the stated issues of expense and selectivity.[42] The bioconversion of HMF to FDCA generally requires a cascade synthesis, involving more than one step for the oxidation of the alcohol and aldehyde moieties (Scheme 3). To date, reported enzymatic syntheses proceed via variations of the strategies outlined in Scheme 3. Enzymes used include: the hydrolytic lipase *Candida arctica* lipase B (CALB);[43,44] oxidases such as arly-alcohol oxidase (AAO),[45–47] galactose oxidase (GO),[44,46,48,49] periplasmic aldehyde oxidase (PaoABC)[49] which catalyse the oxidation using oxygen, and an oxygenase unspecified peroxygenase (UPO).[45,46]

A particularly successful conversion from HMF to FDCA has been documented using a combination of CALB and the stabilised oxygen radical generator 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO).[43] This synthesis gave a high yield of 93%, at a moderate temperature of 40 °C over 24 h, with the added benefit that CALB is a widely commercially used enzyme, offering the potential for an industrially scalable synthesis. Another example reported by McKenna et al. (2017) used a combination of GO, PaoABC, catalase (CAL) and horseradish peroxidase (HRP), producing the FDCA in 100% yield, at 37 °C in just 6 h. While these results are interesting on a laboratory scale, the combination of numerous enzymes complicates upscaling in industry due the requirement to balance enzyme turnover rates, enzyme reusability and the throughput of intermediates. The authors have begun to address some of the issues by enhancing the PaoABC stability, and therefore facilitating its recovery and recyclability.[49]

There are also reports of the enzymatic conversion of furoic acid (Scheme 2) to FDCA via a reversible decarboxylase enzyme.[50] This represents a novel approach with the biocatalytic conversion of furoic acid to FDCA, however the development of this process is still in the early stages.



Scheme 3. Enzymatic routes to FDCA, proceeding via different intermediate compounds, including 2,5-diformylfuran (DFF). Enz, enzyme.

Aminated furfurals

Conversion of HMF by amination to give aminated furfurals is also a promising method of creating sustainable monomers for polymer synthesis. These aminated compounds possess the further benefit of having desirable functionality for pharmaceutical intermediates.[51] The aminated furfurals shown in Figure 3 are closely related to HMF and have different applications in monomer synthesis.

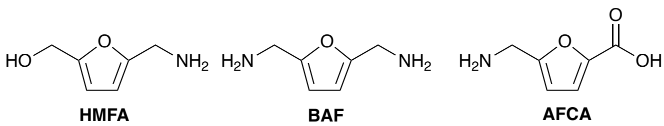
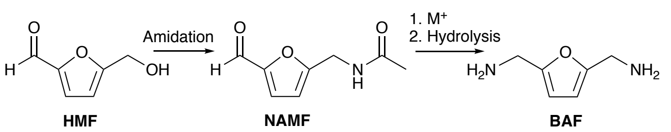


Figure 3. Structures of potential monomeric aminated furfurals. Hydroxymethyl furfylamine (HMFA). Bis(aminomethyl)furan (BAF). Aminofurfuryl carboxylic acid (AFCA).

The conversion of HMF to HMFA chemically requires harsh reaction conditions, often utilising high temperatures or pressures,[52,53] or resulting in a low yield. A recent example has employed nickel-aluminium catalysts, along with a hydrogen environment and 100 °C.[54] However, the use of the biocatalyst transaminase (TAm) has been shown as particularly effective in this reaction. TAms are a highly diverse family of enzymes that have gained significant interest in applied organic synthesis due to their ability to produce amines from ketones or aldehydes. The action of the TAms on the HMF starting material provided high conversions and yields to HMFA under mild reaction conditions.[51]

Furthermore, the synthesis of AFCA (Figure 3) chemically and biocatalytically has been achieved.[51] AFCA is a particularly promising amino acid monomer due to its potential to self-condensate to produce a polymer, and it could also be used as a co-polymer with other amino acid monomers. Its similarity to FDCA, already used in polymer synthesis (Scheme 1), renders it an exciting potential sustainable building block. A multistep chemical synthesis was accomplished from HMF in 2017 by Dunbabin et al*.*, and employed milder conditions than other routes, again typically involving high temperatures and/or pressures as well as metal catalysts.[40,55] The biocatalytic synthesis of AFCA has also been reported using a TAm which worked well on a small-scale test reaction.[51] While the yield for the larger scale enzyme reaction was modest by comparison, further enzyme or reaction optimisation should enhance this.

Bis(aminomethyl) furan, BAF, has the potential to be used as a monomer for polyurethane and polyamide synthesis,[56] as well as a cross-linking molecule between polymer chains. Cross-linking is often necessary in existing polymers to manipulate their properties for a desired outcome, such as enhancing tensile strength to make them more suitable for their anticipated use.[57] To covalently link polymer chains, side chains of the polymer must react with a difunctional reactive species. In this case, the two amines in BAF could create the cross link. Chemical methods of synthesising BAF from HMF often proceed via the intermediate DFF shown in Scheme 3, as direct preparation from HMF has proven difficult due to the numerous side products that occur.[58,59] Reported syntheses use high pressure and temperature,[60,61] with some using a Raney-nickel catalyst, which is undesirable in today's climate due to its toxicity. A recent synthesis proceeded via an alternative route, avoiding DFF formation and via *N*-Acyl-5-aminomethyl furfural (NAMF), produced from HMF, with subsequent hydrolysis to give BAF (Scheme 4).[56] Dunbabin et al., also reported a synthesis however several steps were required.[51]

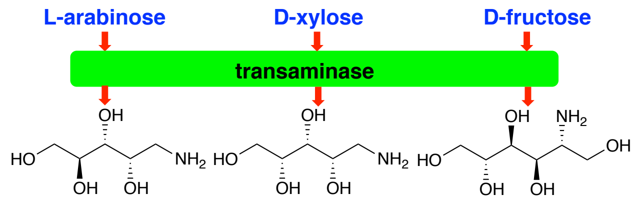


Scheme 4. Wang et al. 2018 synthesis of BAF from HMF, via intermediate NAMF.

A biocatalytic synthesis of BAF has also been achieved and eliminated the need for harsh reactions conditions or toxic catalysts.[51] A TAm was used and afforded BAF in around 50% conversion yield. For upscaling into industry, the yield will need to be improved via reaction or enzyme optimisation.

Aminated sugars

Most material applications of bio-based carbohydrates involve breakdown of the polysaccharides into platform chemicals such as HMF and modification into suitably functionalised building blocks. These include diacids, diols, amino-alcohols and amino-acids. An alternative emerging strategy is the generation of amino-carbohydrates or amino-polyols directly from sugars. A recent report has described the direct amination of 10 sugars using the enzyme transaminase (TAm), including for example L-arabinose and D-xylose which are available from sugar beet pulp waste, and D-fructose (Scheme 5).[62] A range of different TAms were used in the study and a colorimetric screen highlighted which enzymes reacted more readily with which sugar. From this, reaction conditions were optimised to give the amino-polyols in up to 79% isolated yield. This result is very exciting as it opens up a sustainable route to functionalising sugars from sources such as low value sugar beet pulp with sustainable catalysts, for biomaterials applications. A further publication using commercial TAm enzymes for the amination of aldoses was also reported in 2019.[63]



Scheme 5. Amination of sugars to amino-polyols

A related interesting strategy has been described for the production of amino-carbohydrates. Here, enzyme cascades were used to functionalise carbohydrates containing D-galactose, wherein a galactose oxidase was used to oxidise a primary alcohol on the oligosaccharide, and the aldehyde formed was then aminated with a TAm.[64] In all of these aminated sugars the key amine functionality is available for forming bio-materials with more hydrophilic properties.

Polymer synthesis from sustainable monomers

Sustainable polymer synthesis has drawn greater attraction in recent years, with numerous companies across various industries turning their attention to avoiding the use of fossil fuel derived chemicals.[65,66] The monomer FDCA is of significant interest as described above as it is used in the synthesis of PEF. The upscaling of FDCA synthesis to an industrial level has been accomplished commercially and a recent collaboration between industry partners has been funded for a plant to enable an FDCA production capacity of 50,000 tonnes.[67] Numerous other small-scale polymerisations of FDCA have been reported including using cobalt metal catalysts to synthesis an FDCA co-polymer,[53] and a 2 g scale Ugi four component reaction which has the added benefit of high versatility and application to other polyamides.[68] Moreover, the use of CALB in the polymerisation of FDCA has been achieved, at a moderate temperature of 60 °C, with the advantage that CALB is used in a stabilised form that makes it easily recoverable and recyclable on a large scale.[69,70]

While FDCA is a well-researched monomer with many polymerisation procedures reported, the polymerisation of aminated furfurals is less well documented. The polymerisation of HMFA has been reported using CALB at 60 °C,[69] however BAF and AFCA have received less attention. AFCA being an unnatural amino-acid has the potential for self-condensation, and the ability of amino-acids to form polymers has been described. For example, the polymerisation of the naturally occurring amino acid lysine has been explored in detail.[71] Self-condensation reactions are particularly beneficial on a larger scale as they only require one starting material and one reaction step, being typically high yielding. With the multi-functionality of aminated sugars, their potential for use in synthetic bio-based polymers is significant.

Potential for biocatalytic applications

To enhance the use of biomass derived building blocks we need efficient methods for the breakdown of carbohydrates. In addition, the sugars generated need to be efficiently converted into suitable monomers with the appropriate properties using low cost sustainable methods. One approach is the development of better catalysts such as heterogeneous catalysts, and there are continuing efforts to do this. However, their use can still have problems due to sustainability issues or they can generate unwanted side products. An example is the selective synthesis of primary amines from carbonyl compounds where traditional synthetic routes can lead to secondary or tertiary amine by-products. For other compounds such as furans, the reductive conditions can also reduce the furan ring. One solution, as briefly mentioned, is the use of biocatalysts which have many advantages over traditional chemical reagents due to their exquisite reaction selectivities.

The development of successful biocatalytic processes depends on the identification of suitable biocatalysts. Candidates may be discovered by activity screening of cultured strain collections or large metagenomic libraries. Alternatively, advances in next-generation sequencing technologies have in recent years substantially expanded genomic and metagenomic databases thereby accelerating the enzyme discovery. Once the enzyme has been identified, its properties such as enzyme activity, thermostability and tolerance to harsh conditions such as extreme pH and organic solvents, often need to be optimised in order to fulfil the criteria required for use in industrial biocatalysis. Enzymes are optimised through various protein engineering strategies. There are rational approaches for protein engineering such as directed mutagenesis or directed evolution design in which the focus is to generate mutant libraries and probe protein sequence to function relationships.[72] Directed evolution is achieved by creating a high number of protein variants containing random mutations resulting in a mutant library. This random mutagenesis has become a powerful tool in successfully evolving proteins with desired properties, especially those proteins with limited function and structural information.[73] General methods for random mutagenesis include error-prone PCR and rolling circle amplification but one frequently used technique of particular interest is XL1-Red.

XL1-Red is an *E. coli* strain that has been engineered to be defective in 3 primary DNA repair pathways, ultimately leading to elevated rates of spontaneous mutations within a gene of interest following a transformation.[74] This mutator strain is deficient in the DNA repair pathway genes *mutS*, *mutT* and *mutD* (Figure 4) leading to an estimated 5000-fold higher rate of spontaneous mutations compared to that of the wild-type. A major advantage of using XL1-Red over commonly used error-prone PCR random mutagenesis is that XL1-Red mutagenesis is a much simpler protocol with fewer steps involved.[74] Many studies have utilised XL1-Red to engineer different proteins for example, a library of amine oxidases have been generated this way in which a mutant variant was found to increase enantioselectivity towards (*S*)-α-methylbenzylamine.[75]

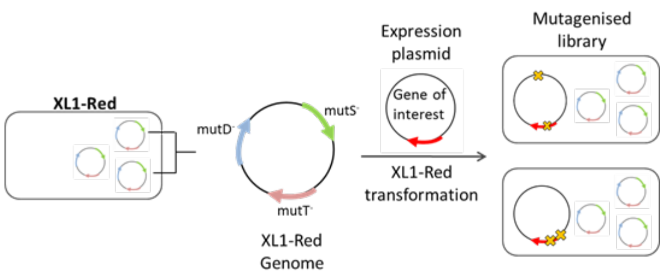


Figure 4. Overview of random mutagenesis by XL1-Red with transformation using gene of interest. The three DNA repair systems which are impaired in XL1-Red strain, mutS, mutT and mutD and mutations in the target plasmid are highlighted here.

Even though random mutagenesis can be a successful application towards improving properties of proteins, there are limitations to this approach when it comes to searching for desired variants from a large pool of mutants. To overcome this, developing robust high throughput screening is essential to maximise the chance of finding desired mutants. Carrying out large scale mutagenesis studies of numerous enzymes requires techniques to be both practical and efficient followed by high throughput colony isolation and screening (Figure 5).

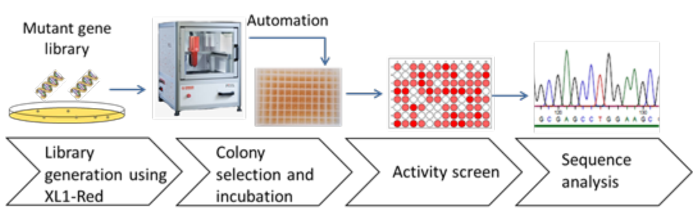


Figure 5. Strategy for directed evolution: library generation by XL1-Red; automated colony picking using PIXL colony picker and growth of mutants in 96-well format; activity screening of mutants; subsequent sequence analysis revealing amino acid exchanges in improved variants.

Enzyme engineering for improved biocatalysis is gathering pace with the introduction of mutated enzymes in industrial processes. One example is the pharmaceutical application in which a biocatalytic cascade was developed for the manufacture of an HIV treatment Islatravir.[76] Enzymes engineered through directed evolution were able to construct the drug from simple building blocks in a three-step biocatalytic synthesis, something that had only been achieved previously with conventional chemical synthesis in 18 steps. It is clear that for future processes, adopting biocatalytic cascades as a sustainable synthesis strategy is essential. Continuous advances in biocatalysis, including the synthesis of building blocks and polymers, will rely upon protein engineering and the discovery of new enzyme transformations.

Summary

With the increasing drive to create more sustainably viable polymers, there is a changing landscape in the area of monomer and polymer synthesis. We are investigating approaches to prepare monomers for polymer synthesis using biological catalysts and also starting from carbohydrate feedstocks derived from waste such as sugar beet pulp, straw etc. This has the additional benefit of creating value from a low-cost waste material. A particular interest is the use of biocatalysts to make furanoates containing nitrogen that will produce materials with stronger bonds and could also act as cross-linking groups. In addition, we are investigating the conversion of sugars into nitrogen containing sugars for use in polymer synthesis or as cross-linking reagents with improved biodegradability properties. Challenges in moving towards renewable-based polymers will include their performance, scalability, cost, and recyclability. Biological routes to polyester formation are also becoming well established to generate biodegradable polymers, highlighting an important shift to such materials. Our reliance on non-renewable feedstock needs to be tackled now to generate the materials of the future and provide impact on moving towards a full-circle renewable system.

Conflicts of interest

There are no conflicts to declare.

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Biodegradable plastics: part of the solution or part of the problem?

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Biodegradable plastics are growing in popularity, both with industry and the public. This is because they are seen as a solution to the problems of plastic waste. However, their environmental credentials need to be more fully assessed, including challenges related to their collection and processing, issues around environmental contamination, and factors regarding public trust and behaviour change. Biodegradable plastics could be part of a sustainable UK packaging system, but only with strong government intervention and the development of technical solutions and financial incentives that make them part of a biodegradable plastic circular economy. This would require: Regulation, testing and labelling of biodegradable plastics; a new automated method of sorting biodegradable plastics from non-biodegradable plastics; a UK-wide system of industrial composters for biodegradable plastics; a UK-wide system of collection for biodegradable plastics; a set of PRN taxes that give biodegradable plastics value as they travel through the biomass circular economy; a public campaign that makes it clear how citizens can dispose of biodegradable plastics. As part of a systems analysis of the biodegradables sector, the Big Compost Experiment online UK citizen science study was launched in November 2019. Here we report our findings, including current citizens' opinions and behavior towards compostable and biodegradable plastics, performance of these materials under home composting conditions, and statistics on UK home food waste practises.

Introduction

In 2018 the UK Plastics Pact set a target to make all plastic packaging 100% recyclable, reusable, or compostable, and to eliminate all unnecessary single-use packaging, by 2025.[1] This declaration has resulted in a significant growth of the compostable plastics packaging sector. New companies are offering a vast range of products that are intended to replace single-use plastic packaging in products that are not suited to recycling due to contamination such as nappies, wipes, and take-away food packaging and ready-meal trays. This global market for compostable plastics was 1.2 million tonnes in 2018 and is set to grow by 60% by 2023.[40] However, there are some systemic problems to solve if this growth is not to result in the unintended consequence of significant environmental damage. These are as follows:

- Biodegradable plastics are currently unregulated; while there are certification standards that can be adopted voluntarily, these do not guarantee specific levels of environmental protection.
- There is no dedicated UK-wide collection and processing facilities for compostable plastics, without which their environmental impact are likely to be high.
- There is currently no working technical solution to the automatic separation and sorting of compostable plastics, thus they are a growing contaminant in the plastics recycling and food waste collection systems.
- There is widespread confusion about what they are and how to dispose of them especially in the case of home compostable plastics.
- There is a growing risk that the confusion around compostable products (and a mistaken belief that they will decompose in any conditions) may lead to increased environmental pollution especially when sold to other countries with no waste collection infrastructure.

In this paper we report on a systems analysis of the biodegradable plastics sector which highlights what is missing from the current industrial composting system and makes recommendation for the design of a new integrated system of design and end-of-life management. In addition evidence from our citizen science project called the Big Compost Experiment, is presented to illustrate the problems and opportunities of home composting. In our discussion we bring the different strands of evidence together to make an assessment of the

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extent to which biodegradable plastics are part of the solution or part of the problem of plastic waste in the UK.

Systems Analysis of compostable sector

Composting standards, processing and labelling

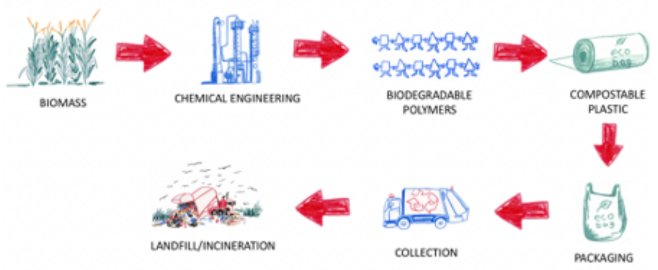
Biodegradability refers to the capability of being degraded by biological activity.[2] Many materials are biodegradable such as paper, cardboard, wood, and certain types of plastic. The word biodegradable does not describe under what conditions and how long a plastic will take to biodegrade. The term 'compostable plastic' is more specific, it describes a material that is capable of undergoing biological degradation in a compost site at a rate consistent with other known compostable materials, leaving no visibly distinguishable or toxic residues.[3] There are two types of composting environment for which compostable plastics are designed, industrial composting and home composting.

Industrial composting is a controlled biotechnological process for transforming biodegradable organic waste into compost, a resource used in agriculture to improve soil.[4] Depending on the process, industrial composting facilities are designed to undertake aerobic composting or anaerobic digestion (biogasification). In aerobic composting, microorganisms consume oxygen while breaking down organic waste to produce CO_2, water, compost, and heat. In anaerobic digestion, bacteria degrade the organic waste in the absence of oxygen, producing biogas (methane and CO_2) and digestate[5] The two different processes are performed in different facilities. Industrial composting facilities digest garden and green waste under aerobic methods, whilst anaerobic digestors normally deal with food waste.[6] Typically these facilities are not optimised to take compostable plastics which are generally removed even at low volumes.[7]

Home composting is a general term for the process by which biodegradable garden waste or domestic food waste is collected and placed in either a container or heap to allow natural processes to turn it into compost. It is a manual process whereby the composition and process temperatures remain largely unregulated. Both aerobic and anaerobic conditions can occur in home composting, although aerobic conditions are more normal. The time frame for home composting depends on personal preference and the use to which the compost is put, but 3-12 months is typical.

Biodegradation testing standards (ISO and ASTM) have been designed to determine the biodegradability of plastics in soil, compost, landfill, marine, or other aquatic environments.[8, 9] The EU standard for compostable and biodegradable packaging EN 13432:2000 defines the criteria that must be met for a material to be suitable for commercial industrial composting:[10] Test material (packaging and organic waste) has to show disintegration and loss of visibility in the final compost; after three months, no more than 10% of the initial weight of the test material should be retained after sieving it through 2mm mesh size. Within a maximum of six months, 90% of the carbon in the test material must be converted to CO_2, having the same rate of biodegradation as natural materials. The test material must have no negative effects on the composting process and no adverse effect on the quality of the compost produced, including the heavy metals content. The standards specify requirements for the identification and labelling of commercially compostable plastics.[10] Although there is currently no international or European standard for home composting, the following national regulations, standards, and certifications exist: UNI 11183 (Italy), AS 5810 (Australia), NT T 51-800 (France), and OK Compost (Belgium).[11] In the UK, the Publicly Available Specifications PAS100 and PAS110 provide a baseline quality specification for compost and digestate respectively. [12]

Figure 1. The current life cycle of most biodegradable plastics



Life cycle of biodegradable plastics

Fig. 1 shows the typical life cycle of biodegradable plastics in the UK, which start life as biomass waste from a crop such as corn, wheat, or potatoes. The chosen crop undergoes chemical engineering treatments to convert its starches and cellulosic material into polymers. Once the basic polymers have been produced they are processed into plastic granules for distribution to packaging manufacturing plants, which use processes similar to those for mainstream polymers such as blow moulding, extrusion, and compression moulding. This is one of the advantages of biodegradable plastics; they fit into existing processing practices for packaging and filling products.

After use, biodegradable plastic packaging needs to be separated from other plastics because biodegradable plastic requires a different processing route. If the packaging is made from an industrially compostable material then it should be separated for that purpose. However, there are very few special collections for these plastics in the UK. In the absence of these they should not be put into recycling systems, because there are currently no automated sorting technologies available for compostable plastics. If compostable plastics are put into the food waste collection, they get separated and burnt, or sent to landfill. This is because food waste is processed using industrial composting facilities and anaerobic digesters. The vast majority of anaerobic digesters in the UK cannot currently digest biodegradable plastics. Even though some biodegradable plastic films can, in theory, be digested, they are too similar to conventional plastics to allow for reliable sorting. Some biodegradable plastics are labelled home compostable but there are little data available as yet about how many people home compost, under what environmental conditions, and whether such plastics biodegrade fully within an acceptable time period (we are in the process of collecting these data through our BIG COMPOST EXPERIMENT discussed later in this paper). Therefore, within the UK, the appropriate waste stream for biodegradable plastics is the general waste, through which they will be sent to landfill or burnt. In landfill, because of the anaerobic conditions, compostable plastics biodegrade slowly over many years into methane, a potent greenhouse gas (some of this is captured and burnt to produce electricity). Incineration converts compostable plastics into CO_2 and water.

If biodegradable plastics end up in the environment, their fate is less certain. Those plastics that end up in the sea may not biodegrade to any great extent because temperatures are generally too low.[13] Those that end up on land may biodegrade if the temperature and humidity are favourable, although this may take many years and leads to microplastics in the environment. Napper and Thompson[13] compared many biodegradable bags in different scenarios and concluded that "none of the bags could be relied upon to show any substantial deterioration over a 3 year period in all of the environments."

Environmental impact of biodegradable plastics

Due to the source of their carbon being waste biomass, the Global Warmng Potential (GWP) of compostable plastics tends to be lower than petrochemical sourced plastics.[14-18] However there can be unintended consequences of using them. For example, for applications where material strength is essential, less plastic is required if it is stronger or stiffer per weight. For conventional plastics optimised for their material properties this equates to less production activities being required which lowers the GWP value due to lower power consumption. Less mass also means less energy usage for transportation, which also equates to a lower GWP. This is why compostable products such as packaging, cutlery, and containers can exhibit higher GWP than conventional plastics, even when taking into account their CO_2 sequestration.[19]

Life Cycle Assessment (LCA) studies show that mechanical recycling of plastic (as an end-of-life option) has a lower GWP than biodegradation, or energy generation.[20, 21] This is because recycling plastic has a lower GWP than manufacturing new plastic. When analyses consider the amount of greenhouse gas emissions that are avoided due to recycling, the net GWP associated with a product is lowered. In addition, most biodegradable plastics require industrial composting to biodegrade and must therefore be collected for degradation.[22] As with plastics collected for recycling, transport and energy are required for biodegradables' waste management, which results in additional CO_2 emissions. Only when full biodegradability in nature is assumed, do biodegradable plastics generate lower overall GWP than recycling conventional plastics.[23]

Recent studies have found environmental impact trade-offs when switching from petroleum-based plastics to bioplastics.[16, 18] In most circumstances, the use of plant-based feedstock has greater environmental impact on: soil acidification, ecotoxicity, eutrophication, and ozone depletion production.[16, 18] Thus the choice of replacing conventional plastics with bio-based plastics depends on which environmental impact category is of most concern. This will depend on the local environment in which processes are to be carried out, in order to determine which environmental impact should be minimised.[24]

Plastic leakage into the environment is a case in point. The durability of conventional plastics (in large form) and its fragmentation into microplastics (plastics that are < 5µm in diameter) endanger wildlife, marine life, and human health.[13, 25-27] This has prompted the rise in popularity of biodegradable and compostable plastics. However, biodegradability and compostability are dependent on environmental conditions; they may behave like conventional plastics and simply fragment.[28-30] Recent studies have shown that both conventional and biodegradable microplastics are harmful to the health and behaviour of small organisms such as earthworms and various marine organisms.[24, 31] However, the extent of its effects depends on the polymer itself and the amount of plastic; the concentration of microplastics used in these studies may not reflect real environmental settings. In addition, because all plastics require additives to support their material functionality, it is uncertain whether their harmful effects are due to the additives or polymers themselves.[32]

Behaviour Change

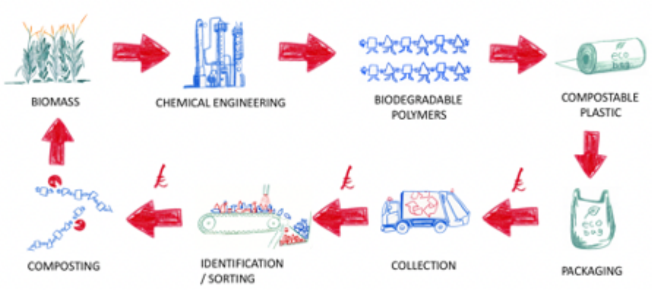
Most people are motivated to do the right thing by the environment and the planet. This means that they are more likely to buy and use materials that appear to be less harmful to the environment. The growing popularity of biodegradable plastics is an example of this – "bio" sounds natural rather than artificial/chemical, and "degradable" sounds good, especially given the awareness of non-degraded plastics polluting our oceans and harming fish and other ocean life.

The main barriers to engaging in behaviours thought to be kind, or at least less harmful, to the environment are capability, especially knowledge about what to do and how to do it, and opportunity, in particular easy access to, for example, a separate collection for biodegradable plastics at no or minimal cost to the behaviour.

There is a danger that biodegradable plastics may cause more harm than good if people believe them to degrade naturally without specialised processing. Currently, there is little awareness that specialised collection and processing is necessary. In particular, there is a potential moral hazard at play whereby those who sell compostable packaging as a solution to the plastic waste crisis may be relying on the public's ignorance of the specialist collection and processing methods that are necessary for it to be a sustainable option. If the sector grows without the public being well informed, there is a real risk that littering such plastics into the environment may increase.[33] A persuasive example is the growth in the sector of biodegradable wipes where, without clear messaging, people believe that wipes are suitable for disposal directly into the environment, or down the toilet.

Biodegradable plastics are increasingly viewed as a 'green' alternative to unrecyclable polythene films such as those used to package weekend magazine supplements (for example, Weekend, The Guardian's Saturday magazine) or membership magazines (for example, Tate Etc.). In cases such as these, organisations are responding to public pressure to do something better for the environment by swapping one plastic for a "better" one. However, a more environmentally sustainable approach would be to remove the plastic packaging altogether. These examples highlight another behavioural danger associated with biodegradable plastics: they appear to provide a greener approach to the "throw away" culture of single-use plastics. Other examples are compostable cups and compostable take-away containers, which are displacing more environmentally beneficial reusable or recyclable alternatives.

Figure 2. A circular economy of compostable plastics (the £s indicate which parts of the system would need a packaging PRN tax to make it viable).



A circular economy of biodegradable plastics

The UK government has recently convened consultations on changing its plastic waste management strategy. In particular, the Packaging Recovery Note (PRN) scheme is being reconsidered after criticism that the existing system only covers 10% of plastic packaging recycling costs and is vulnerable to fraud.[34] There is also a growing problem around the Packaging Waste Export Recovery Notes in that it is increasingly difficult to find reputable waste processors in other countries, especially in light of the fact that several countries have stopped accepting plastic waste exports altogether.[35]

From a financial perspective, in order to create a circular economy for biodegradable plastics, it is necessary to improve the profitability of the packaging system. For biodegradable plastics to work within a circular economy, the costs of collecting and composting them either need to be paid by the proceeds of the sale of the compost (this currently has a negative price and is given away), or by taxes or other fees. To address this, the revised PRN scheme for biodegradable plastics would need to ensure that some of the collected revenues are ring-fenced for improving waste collection, sorting, and industrial composting (see Fig. 2). This could make biodegradable plastic anaerobic waste management comparable with the incumbent solution, incineration, which has gate fees of about £90/tonne as of 2019, and with £100/tonne for landfill.[36] The revenue from this tax could be structured as a co-finance mechanism for potential solutions to be invested in new waste management solutions.

Big Compost Experiment

The Big Compost Experiment was created to collect data on the public's attitudes to, and understanding of, biodegradable plastics and home compostable plastics in particular. Another aim of the Big Compost Experiment is to ascertain whether home compostable plastics do compost in the range of conditions found across the UK.

The study was designed with citizen science principles at its core,[37] and aims to facilitate a wide range of participant involvement. The format consists of a publicly accessible website (www.bigcompostexperiment.org.uk) containing a 5 minute online survey, and an optional home composting experiment facilitated through an online personal login facility. The website also contains additional educational information and links on biodegradable plastics and composting, and a social media blog, to raise public awareness of plastic waste issues. A range of participant recruitment methods were used in order to address data bias and to engage a wide range of participants from groups frequently excluded from participation in scientific activities, such as people from deprived communities, or specific ethnic groups. Methods included interviews on national and regional radio (BBC Radio 4 Inside Science, Cambridge 105), articles in national charity and organisation magazines and on social media platforms (including Science World, National Allotment Society, Garden Organic), and public outreach events with schools and charities.

Method Part 1 – Online Survey

Before participating, citizens are directed to the Participant Information and Consent information which gives information about the project aims, data protection, image guidelines, health and safety advice, where to direct questions or complaints. Ethics Approval for the study was granted by the UCL Research Ethics Committee (Project ID/Title: 16747/001: Big Compost Experiment) until 07 November 2021.

The survey begins with illustrated questions enquiring about opinions and behaviours surrounding biodegradable plastics and food waste. At this point a participant has the option to end participation in the survey and to submit their responses anonymously. If a participant chooses to continue they are provided with further illustrated questions enquiring about the type of composter they use and their composting habits. At the end of the survey a participant is given the option to end participation in the survey and to submit their responses anonymously. At this point a participant is also given the option to take part in a home composting experiment, facilitated through setting up an online login account and provided with PDF instructions on how to carry out the experiment.

Method Part 2 – Home Composting Experiment

Participants are offered the option of taking part in a home composting experiment by setting up a user login account with which to share their experiment setup and to record their results. The account setup asks for their contact email, information about their composter type and postcode location (first three letters of their post-code, giving only general information about which area they compost in) with the option to display this on a map of the UK, the method of composting and the usual time taken to make compost in their composter, what organisms live in their composter, and to select and log a range of biodegradable plastic items they wish to test, and the rate at which the item degraded in their composter. Participants can select the type and quantity of biodegradable plastic item(s) from an illustrated list that they would like to test, such as "cutlery", "cups", "shopping bags, and "newspaper wraps". Participants are advised to only test items that display the following manufacturer information:

- 'compostable' (only)
- 'home biodegradable'
- 'home compostable'
- 'suitable for home composting'
- TUV OK Compost 'HOME' label

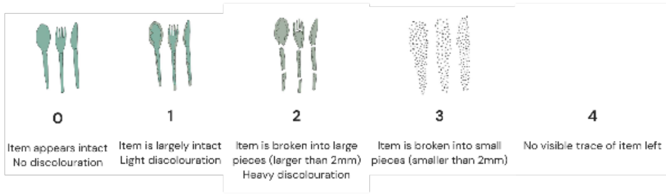
Participants can then submit details about their selected item(s) and the length of time they wish to run their experiment for, based on how long it usually takes them to make compost. Participants are also given the option to submit photographs of their home composter and/or items with the option to display them on the public website Gallery, see Figure 3. The Big Compost Experiment website automatically logs this information to a database and is used to setup an automated email reminder for participants to report their results at the end of their experiment.

Figure 3. Examples of uploaded home compost experiment images showing participant composter, experiment items and results.

Method Part 3 – Reporting

Participants are sent an email once their experiment is complete with a request to search for traces of their item(s) in their composter. Experiment Guidelines recommend using a household spade/trowel and sieve to look for the items in their compost, and are advised that under 18s must be accompanied by a responsible adult. Participants are advised to collect any traces of their items they can find (if there are any), compare them with a 'Degradation Scale,' see Figure 4, and record any other useful observations about their item(s) via their user login account. A participant also has the option to upload image(s) of their item results. Once a participant has completed their experiment and reported their results, disposal of items in general waste collection is advised.

Figure 4. 'Degradation scale' provided for participants to compare and analyse their experiment results.



Interim Results

The data analysed in this paper were collected from November 2019 to January 2020, during that time 4100 participants from across the UK completed the attitudes survey, 836 of which engaged actively in a home composting experiment. The distribution of these participants across the UK is shown in Figure 5 showing good coverage across the UK, with the highest proportion the midlands and the south. This roughly correlates with the distribution of population density in the UK. 90% of these participants indicated that they separate their food waste, this is a much higher than the UK average[38] and is strong indicator that this is a biased sample.

In answer to the question "Are you more likely to buy products with packaging marked 'compostable' or 'biodegradable'?" 84% answered "yes", 8% answered "no" and 8% answered "don't know" as shown in Figure 6. The high proportion of "yes" is another indication that we have biased sample. It is likely that the people attracted to take part were those who are already interested in composting, evidence for this is that 74% of our participants use home composting which compares with a national average of 34%.[39]

When participants were asked which food waste strategy they use to dispose of biodegradable plastics, if any, 15% answered "using council organic waste collection", 41% answered "using home composting", and 4% answered "using another organic waste strategy" as shown in Figure 7. Although another indication of a biased sample, the range of disposal methods for biodegradable plastics highlights the need for further systems analysis of the impacts of these materials on a range of domestic and industrial scale organic waste processing.

The participants use a wide variety of composters ranging from indoor wormery to outdoor trenches, with the most popular (65%) being an outdoor closed-bin composter (see Figure 8 for the distribution). When asked what use they put their compost to (with multiple answers allowed from a suggested list), 82% replied that they used it to enrich their soil to grow edible plants, fruit and vegetables (see Figure 9). This is important as it indicates that the food chain, albeit a home-grown one, is affected by whatever substances are put in home compost.

The importance of home composting not just as a means to enrich soil but also as an important site of biodiversity is confirmed in Figure 10 which shows that 14 categories of organism are visible to the naked eye in the home composters, from worms, to mites, to fungi. It is this ecosystem of organisms that is responsible for biodegrading items put in the composter, including the range of compostable plastics tested in this experiment.

1000 participants engaged in our home composting experiment, many of whom recorded what they put into their home composter by uploading a photo of that item to the Big Compost Experiment website (these are shown on the Gallery tab of the website). These images show that, despite our best efforts to guide the participants only to try to home compost items marked clearly as ‘home compostable’, many items that are marked as industrially compostable or just as biodegradable have been entered into the experiment. The number of these items such as cups, forks and packaging is high, and clearly indicates that there is confusion in identifying what should and should not be put in a home composter.

When asked how long it usually takes to make compost in order to set the duration of the home compost experiment, 6% participants selected “3 months”, 200 selected “6 months”, 160 selected “9 months”, 24% selected “12 months”, 12% selected “longer than 12 months”, 9% selected “unknown” (see Figure 11). Composting duration varies depending on type of system used. Systems such as hot composters or indoor wormeries are generally more environmentally controlled, and can create compost in 3-6 months. Other systems such as outdoor compost heaps or open composters usually take longer, between 6 and 12 months to fully compost organic matter. In addition, other factors affect the rate of biodegradation such as temperature, humidity and other environmental factors.[8] This suggests current home composting certification test criteria may not reflect the variation in composting practices across the UK.[11]

Due to the variations in home compost experiment duration, we did not expect many results to be ready after 3 months. We do have a small number of completed experiments, with other remaining experiments ongoing. Nine experiments were completed with the participants rating the degradation of each using the scale shown in Figure 4. One item was reported as “no visible trace of item left” (a shopping bag using an outdoor multi-stage composter); all the others were still visible, as shown in Figure 12.

Figure 5. Online map showing distribution of home composting experiments across the UK.

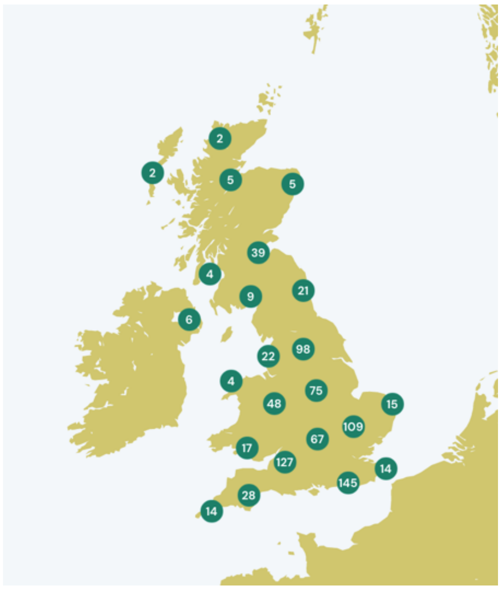


Figure 6. ‘Are you more likely to buy products with packaging marked ‘compostable’ or ‘biodegradable’?’. Values calculated from 4100 participant responses.

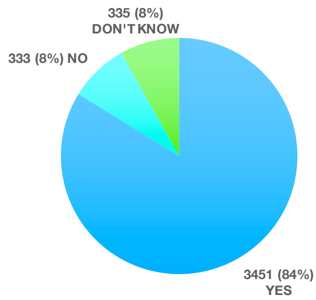


Figure 7. ‘Which of the following do you use? (indicating which you use to dispose of biodegradable or compostable plastic)’. Values calculated from 3706 participants that separate food waste. Multiple responses included, null responses not shown.

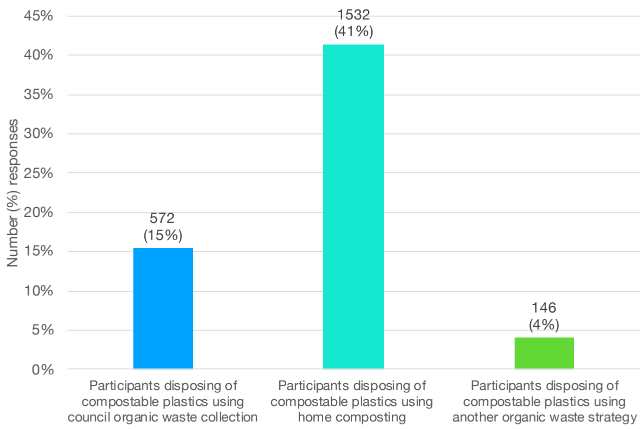


Figure 8. 'Which types of composter do you use?' Values calculated from 3035 participants who home compost. Multiple responses included.

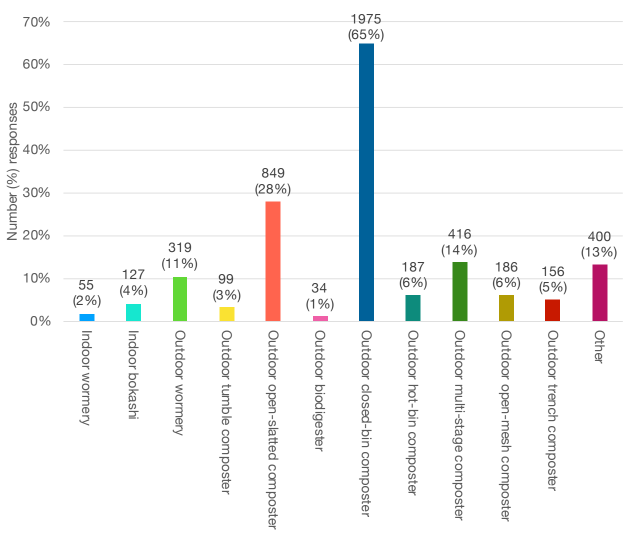


Figure 9. 'What do you use your compost for?'. Values calculated from 3035 participants who home compost. Multiple responses included.

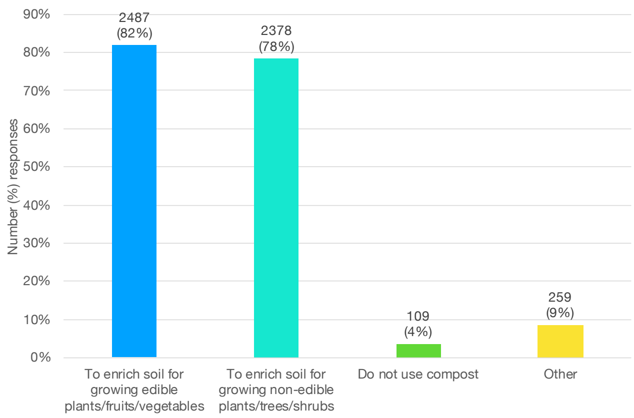


Figure 10. 'Have you seen any of these living in your composter?'. Values calculated from 3035 participants who home compost. Multiple responses included.

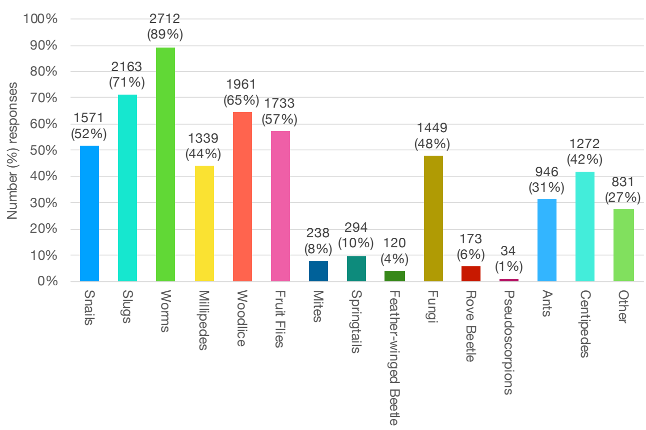


Figure 11. 'How long does it usually take you to make compost?'. Values calculated from 836 home compost experiment participants.

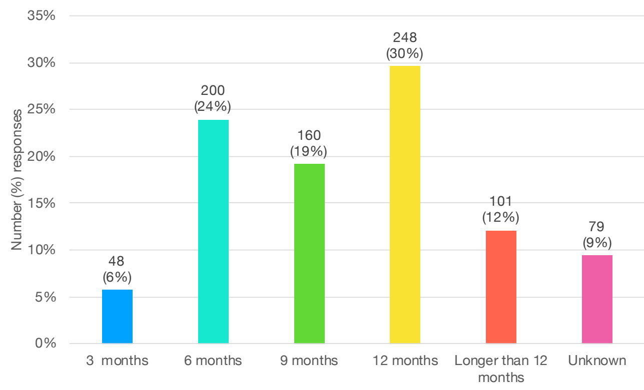
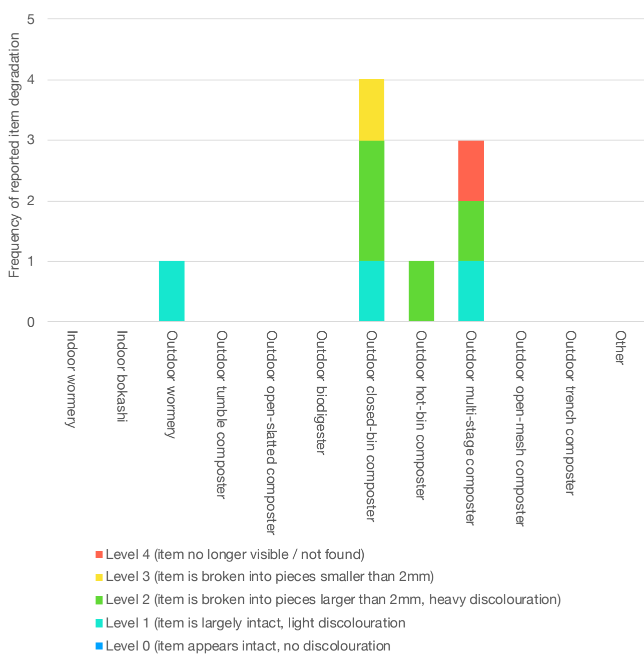


Figure 12. Frequency of item degradation scale reported arccording to composter type.



Discussion & Conclusions

The words "biodegradable" and "compostable" are often used interchangeably – even by packaging manufacturers – but have very different meanings. "Biodegradable" is a general term used to describe any substance that can be consumed by biological organisms. "Compostable" describes a material that will biodegrade under a specific set of circumstances. There are clear standards for creating compostable plastics, but manufacturers are not legally obliged to adhere to them, nor to label the ingredients of their products, or test their impact on the environment. Despite the confusion, many companies have swapped to packaging they describe as biodegradable or compostable because they believe their customers want more sustainable packaging. Our preliminary results from the Big Compost Experiment survey, although clearly from a biased sample, do not contradict this assumption, with 84% stating they are more likely to buy products marked biodegradable or compostable. This is evidence that the compostable plastic sector is likely to grow.

This idea that a material can be sustainable is a widespread misconception. Only a system of production, collection, and reprocessing of a material can be sustainable. Even the type and amount of energy used to fuel the process, the water usage, and the by-products contribute to its environmental footprint. This applies to compostable plastics as much as normal plastics. Although the bio-sources of compostable plastics make this class of material more renewable, the fact that there is no UK-wide system of collection is problematic. Most compostable plastics end up in landfill or are burnt. Some people put compostable plastics in their food waste collection, but this is a contaminant and increases the costs of current anaerobic digester systems. Anaerobic digesters are not optimised to take biodegradable plastics, which are instead removed and sent to landfill or burnt. If they end up in the environment, especially in rivers or the sea, the evidence shows they are likely to be there for many years.

The economics of creating a sustainable biodegradable plastics packaging system should not be ignored when considering the future of packaging. At present, companies can become profitable by making these plastics from agricultural waste products, but this does not include the full costs of a UK-wide system of collection and the running costs of industrial composting plants. Such a system would need a method of reliably sorting and separating biodegradable plastics from other plastics, as well as from food waste. This does not currently exist and would need further research and development to be implemented.

The current instructions for recycling are already complicated and depend on your location within the UK; many people feel unable to understand them. In terms of behaviour change, it is vital that we simplify the actions required of people; introducing biodegradable plastics does the opposite. Even if there did exist a UK-wide collection and processing system, it would still rely on individuals to do the right thing. This would require much better labelling and a concerted public campaign. The preliminary results from our Big Compost Experiment show that even with a sample of motivated participants enthusiastic about compostable plastics, there is confusion about what is home compostable. A great many items labelled compostable or biodegradable such as those made from PLA have been put into the home compost of the participants. These are designed to be industrially composted, but the labelling is clearly not working for many of the participants in our study.

The range of item degradation results shows that the biodegradation process for home compostable plastics in home composting practices is complex and presents challenges for the regulation and certification of home compostable materials. A significant challenge is the diverse composition and form of biodegradable plastic products and packaging being marketed as home compostable and thus the complex mix and volume of polymers ending up in home compost. We know from our survey that the compost produced goes into the food chain of UK citizens. Even if some home compostable plastics are shown to fully compost in all UK home composts, it would be wise to assess the environmental impact of these materials, the viability of using home compost to properly dispose of biodegradable plastics, and to establish which product and packaging applications and polymer types are suitable for this method of disposal.

With all these issues in mind, it is worth asking the question: What problem do biodegradable plastics solve? The bio-source of their carbon moves the packaging sector away from petrochemicals and towards a more sustainable future. But this is also true of bioplastic versions of PE, PP, and PET, which are fully recyclable, as well as being compatible with the current collection and sorting systems in the UK. Biodegradables are useful for some product types that are not suited to recycling due to contamination such as nappies, wipes and feminine hygiene products. These products typically end up in landfill and, if the use of biodegradables were to divert them into a circular system of composting, then this is likely to be a better outcome. However, such a system would require a large infrastructure to support it and a reformed system of PRN to make it economically feasible. Our results suggest that some sectors of the public are in favour of biodegradable plastics. In order to understand this in more detail further behavioural analysis is needed to fully assess public capability, motivation, and opportunity in relation to biodegradable plastic use.

Despite the range of participant recruitment methods used, the results indicate a bias towards participants who already separate food waste. This could suggest that people who are engaged with issues related to food waste and the environment are more motivated to take part in this study than those who are not. As the study is ongoing (until 2021), this will be addressed by carrying out further participant outreach and recruitment activities.

Overall this study suggests that without a system in place either for home composting or industrial composting of biodegradable plastics, biodegradable plastics will be a growing problem. Further investigation is needed into what UK waste processing system needs to be in place for such products to be sustainable, how such a system might operate, and how it could be economically viable. In particular, assessment is needed of the feasibility of using a UK food waste collection system or home composting as the means to harvest biodegradable plastics from domestic households.

Conflicts of interest

There are no conflicts to declare.

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Session 3: Recycling

Mechanical recycling of multilayer packaging materials (MLP)

Manu C. Mulakkal[a], Ambrose C. Taylor[b], Bamber R.K. Blackman[c], Soraia Pimenta[d], Daniel S. Balint [e] and Maria N. Charalambides[f]

Plastic pollution is one of the biggest societal challenges, and as a result plastics are seen in a negative light. Food packaging is one of the many applications, where different types of functional plastics are combined in a laminate form to produce multilayer packaging (MLP) materials which help to preserve and extend the life of food items. However, such multilayer plastic films are extremely difficult to recycle, consequently MLP is typically landfilled or incinerated. This study reports on the feasibility of mechanical recyling solutions, specifically (i) combined melt-processing of MLP plastics and (ii) layer separation (delamination) to improve the recyclability of MLP laminates. The recycling of MLP through melt blending is currently limited due to the low miscibility of polymers used in packaging, which leads to inferior mechanical properties in the recycled polymers. Adding compatibilisers (surfactant polymers) has been shown to improve the mechanical properties. A finite element (FE) based micromechanical model was developed to capture the influence of compatibilisers on the polymer blends. This model can be used as a tool to aid the design of recycled materials from MLP through predicting bulk properties based on the blend composition and microstructure. Limiting the adhesion between the layers such that they can be easily separated during the shredding and washing stages in recycling is another attractive option, as this will allow the separation of metallic/metallized layers which often degrade the mechanical properties of recyclates from MLP laminates. Therefore, two MLP designs permitting the separation of layers were considered. Improving the recyclability of MLPs is crucial in diverting them from waste and rendering them as a viable resource for reuse.

Introduction

Their versatility and low cost have enabled plastics to perform a multitude of functions and as a result they are widely utilised in many industries such as packaging, which accounted for 30 % of global plastic production in 2017[1]. This profusion of cheap plastics has also enabled a throw away culture which has resulted in an abundance of plastics discarded in our environment as waste leading to pollution. As we are becoming increasingly aware of the adverse effect of plastic pollution, efforts to stem plastic pollution in our environment are underway following the eliminate, reduce, reuse and recycle mantra. However, the demand for increased plastic production and plastic industry itself are projected to grow despite the current efforts to eliminate plastic pollution. This is due to several factors such as greater demand for products and convenience in consumption facilitated by plastic packaging. Even though we have not exhausted all the options in eliminating or reducing use of plastics in packaging, they are indispensable in some applications.

Multilayer packaging (MLP) materials are one example where elimination or substitution of certain plastics is inadequate to meet all the packaging functions. MLPs are essentially layers of different plastics stuck together in a laminate form where each of the layers offers unique features to meet various requirements of the packaging function. These functions range from offering mechanical support, barrier protection (against light, humidity and oxygen), printability (for branding and communication) and sealability (to form closed packaging). Figure 1 shows a typical construction of MLP. In light of increasing plastic pollution, waste plastics are seen as a valuable resource, and there is a general consciousness to move towards a circular economy where no materials end up as waste. Currently, MLP is not recycled but ends up in landfill or is incinerated like other flexible plastic packaging leading to loss of material and potential for leakage back into the environment[2]. This paper briefly outlines the challenges in recycling MLP and presents some solutions and tools to enable their effective recycling within mechanical recycling. These

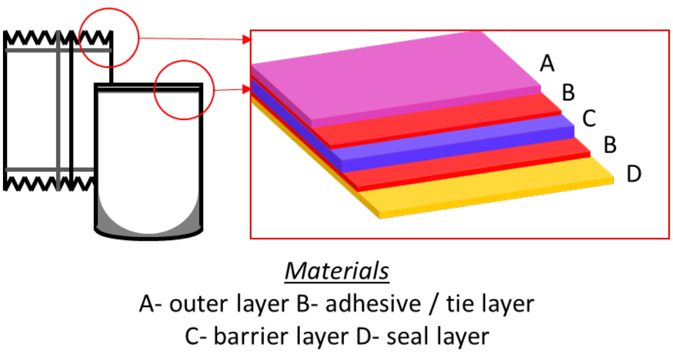

Figure 1: Schematic of multilayer packaging (MLP) laminate

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solutions are envisaged to enable recycle friendly MLP designs and combined processing of mixed plastics.

Challenges in MLP recycling

Although recycling of high value plastics of single polymer types is well established, this cannot be extended to MLP for some inherent reasons. The recyclate retains its highest economic value when it is clear and of single polymeric origin. The combined melt processing of mixed plastics of different types and colour results in a low value recyclate with poor mechanical and physical properties which has limited application[3]. Inability to separate the different polymers in MLP limits its processing to combined melt processing which typically results in low performance due to the incompatibility between the different polymers[4]. Metallised flexible packaging such as crisp packets are of great concern as combined melt processing results in the metallic components forming inclusions within the polymer matrix which leads to premature material failure[3]. The limitations within current sorting technologies such as near infrared (NIR) means good quality MLP and flexibles cannot be sorted from mixed waste, which is yet another challenge that affects the quality of recycled materials made from MLP.

Mechanical recycling

Melt-blending

Mechanical recycling involves shredding the sorted plastics into smaller flakes ranging from 1-3 mm in length followed by melting and extruding into pellets for reuse[2,5]. The plastic products currently recycled at material recovery facilities are recycled in this manner and thus is the prominent form of recycling. Exploring MLP and flexibles recycling solutions within this established recycling infrastructure will have significant cost benefits. Compatibilisation is an option within melt blending that can be effectively applied to immiscible polymer blends to overcome the low mechanical properties arising due to incompatibility and weak interface adhesion[2,6,7]. Here, a surfactant polymer (compatibiliser) is added to affect the interface boundaries, such as the reduction in interfacial tension between the constituent phases, and improves the strength of the interface[8,9]. This process has been widely explored to create polymer alloys with desirable properties of the encompassing polymers and is now being increasingly looked at as a potential solution to address mixed plastics waste fractions. Even though there are different types of compatibilisers available to choose from, they are most effective when selected specifically to compatibilise known polymers in blends where their proportions are known[10]. Whilst there have been many studies into identifying and developing compatibilisers for different polymer blends, the whole process is very experimental, time consuming and onerous. There is a lack of modelling efforts to supplement the experimental work required in identifying the best compatibiliser and its proportions for known polymer blends. The following section will evaluate the feasibility of finite element (FE) based micromechanical modelling to predict the mechanical properties of compatibilised polymer blends.

Finite element micromechanical modelling

Since compatibilising polymer blends effectively changes the microstructure and the interface properties of the encompassing polymers, micromechanical models can be employed to capture the microstructure – bulk property relationship[11,12]. Figure 2 shows the development of a representative volume element from an SEM image of a compatibilised polymer blend. Compatibilisation can be treated as an adhesion problem between the phases at microstructural levels. The adhesion parameters between the phases could be adjusted to capture the effects of compatibilisation. A tensile test was simulated using the model to extract homogenised material properties such as tensile modulus and yield strength. These were then compared to the experimental results found in literature[13] to validate the models. Preliminary studies indicated good agreement between the mechanical properties extracted from the micromechanical FE model and experimental results reported in literature for an 80/20 polypropylene (PP)/polyethylene terephthalate (PET) blend[13] demonstrating the feasibility of micromechanical modelling to capture the effect of compatibilisers. It is envisaged that adhesion parameters for specific compatibilisers can be experimentally obtained to calibrate the developed models. This type of modelling work can offer a virtual testing platform to replace trial-and-error empirical approaches to better inform compatibiliser choices for optimising the mechanical properties of recycled polymers.

MLP designs for ease of recycling

There have been many guidelines to enable recycle friendly designs for products across many industries such as packaging, electronics and fast-moving consumer goods (FMCG)[14,15]. These are primarily aimed to simply the recycling processes to enable maximum material recovery and maximum value for the recyclates. Since uncontaminated recyclates of single polymeric types are highly sought after in the market, there are

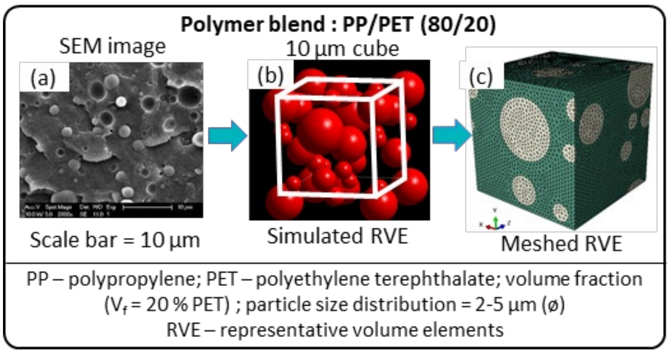

Figure 2: Steps involved in development of finite element (FE) micromechanical model. (a) microscope image of the blend microstructure reproduced from[7] with permission from Carl Hanser Verlag GmbH & Co.KG, München, (b) Simulated 3D microstructure from 2D microscope image, (c) meshed input model for commercial finite element analysis software

advantages to enable separation of MLP layers without compromising their overall functionality. There are several approaches developed to this effect by targeting the adhesive layer. Although there are several options described in patents[16–18], these have not really emerged as mainstream solutions utilised in MLP construction.

Shredding and washing processes are typically employed at the material recovery/recycling facilities (MRF) during the recycling process to produce sorted plastic fractions[2]. Therefore, it is advantageous to utilise the shear forces involved in these processes to enable separation; this will lead to a better integration of any new MLP design with existing recycling infrastructure. Manipulating adhesion between the layers is a simple way to separate the layers, and two different approaches were explored in redesigning MLP construction to enable separation during recycling steps: (1) laminates with localised adhesion through controlled surface treatments, and (2) laminates with water-soluble thermoplastic adhesives. These are briefly discussed in the following sections. Enabling layer separation is crucial in removing problematic layers such as metalized polymers, foils and even printed layers from recycling streams to generate the highest quality recyclates.

Selectively adhered laminates

During lamination, individual layers undergo surface treatments (plasma or corona discharge) to enhance the adhesion between the layers in MLP[19]. In this approach, a patterned substrate mask was utilised to confine the surface treatments to the patterns as opposed to uniform application. Shredding the laminates will release the unstuck layers which can be separated in a sink-float system. The patterns were designed and evaluated with the help of FE analysis to ensure comparable mechanical performance to that of the laminate with uniform adhesion. Preliminary work yielded selectively adhered MLP laminate configurations where the points of adhesion were limited to the surface patterns created with the mask. Figure 3 shows a schematic of this concept.

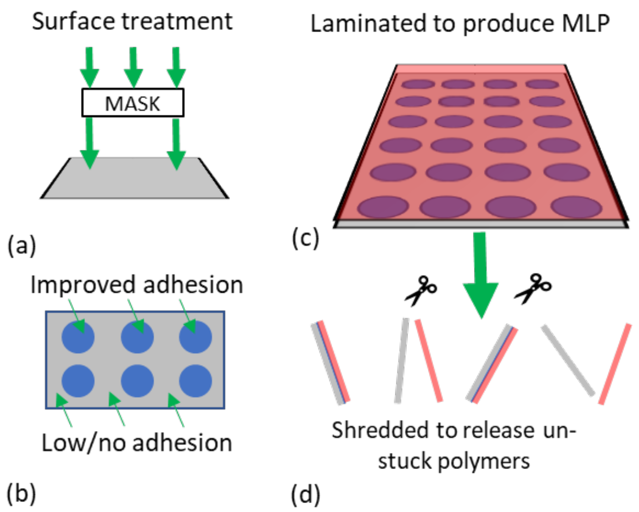

Figure 3: Schematic of the steps involved in the manufacturing of MLP with selective adhesion. (a) Surface treatment of laminates using mask, (b) Localised surface treatment, (c) lamination with another layer to produce MLP, (d) shredding to release stuck and unstuck layers

Laminates with water-soluble thermoplastic adhesives

Co extrusion of different polymers in a layered structure is a common manufacturing route for MLP and there is scope for surface treatments to improve adhesion between the layers. Here, adhesives or a blend of adjoining polymers are coextruded to ensure adhesion between the layers. Therefore, feasibility of a thermoplastic polymer with desirable features such as extrudability (shear thinning) and water solubility were explored to be used as an interlayer adhesive. A commercially available PVOH based polymer was utilised in this study. For reference, this material is very comparable to the water-soluble support material used in 3D printing. Preliminary results from this research are promising as the laminates manufactured (at lab-scale) with this adhesive material were able to be separated into their constituent layers after soaking in water over a period of 24-48 hours at the first attempt. This duration can be brought down considerably by shredding the laminates into smaller pieces to create more access points for the water thereby reducing the diffusion path length, and by adding detergents to act as surfactants.

Conclusions

The complexity of multilayer packaging (MLP) construction has increased to meet more demanding environmental conditions such as in the Tropics. Monomaterial substitutions are not always feasible to address the challenges of recycling. Therefore, it is imperative to develop recycling technologies to address MLP and other flexible mixed plastics that are discarded as waste and potentially become pollutants. Both melt processing and layer separation techniques have merits in enabling effective recycling of MLP. Ideally, packaging products must be developed with ease of recycling and value retention as a priority. To improve the recyclability of MLP and divert these resources from waste, it is essential to further develop these solutions and support material design tools so that they can be successfully implemented at a larger scale.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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Chemical Recycling of Polyethylene Terephthalate (PET) by Monomerisation with Low-Cost Ionic Liquids and Water

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- ✓ Low-cost catalysts/solvents
- ✓ Easy preparation
- ✓ Complete PET consumption
- ✓ High TPA recovery yield
- ✓ High purity TPA

List of Abbreviations

DBN	1,5-Diazabicyclo(4.3.0)non-5-ene
EG	Ethylene glycol
HDPE	High-density polyethylene
Hmim	1-methylimidazolium
IL	Ionic liquid
LDPE	Low-density polyethylene
MLP	Multi-layered packaging
MSW	Municipal solid waste
PC	Polycarbonate
PE	Polyethylene
PET	Poly(ethylene terephthalate)
PHA	Poly(hydroxy alkanoate)
PHB	Poly(hydroxy butyrate)
PLA	Poly(lactic acid)
PMMA	Polym(methyl methacrylate)
PP	Polypropylene
PS	Polystyrene
PVC	Poly(vinyl chloride)
PU	Polyurethane
TPA	Terephthalic acid

Abstract

We generate millions of tons of short-lived plastic materials that rapidly become waste and often accumulate in the environment.[1] Poly(ethylene terephthalate) (PET) is one of the most common plastic materials in use, representing *ca.* 13% of global plastic production.[2] It is a non-biodegradable polymer that is used to make a wide range of beverage bottles, food packaging and textiles, therefore its recycling is a topic of great interest. Mechanical recycling of PET is practised but has challenges with maintaining material properties such as strength and transparency, leading to material losses along the mechanical recycling chain. Chemical recycling *via* monomerisation can overcome these challenges. Monomerisation involves the breaking down of polymers such as PET into their building blocks (called monomers) or into short chains of monomers (oligomers) which can be re-polymerised to yield recycled polymer with essentially virgin grade material properties.[3] Ionic liquids (ILs) are liquids completely composed of ions,[4] are interesting novel media for carrying out PET monomerization, as they have attractive properties, such as low volatility and can be tuned to suit an application. The use of ILs for the depolymerisation of PET was firstly reported in 2009 and used expensive ILs[5]. With our research, we are investigating the use of low-cost ionic liquids for the depolymerisation of PET and the subsequent recovery.

Introduction

Since the discovery of the first synthetic plastic, ‘Bakelite’, invented by Leo Bakeland in New York in 1907, these composite synthetic materials have found their way into all aspects of modern life and industrial activity, serving as every-day commodity materials and devices as well as in construction, packaging, automotive, aeronautic and healthcare applications (Figure 1).[6]

Figure 1. European plastics distribution per intended application in 2018.

Plastics have become a common workhorse material of the modern economy and its use is integral in today’s societies.[7] In the EU, the plastics sector employs 1.5 million people and generated a turnover of EUR 340 billion in 2015.[8] Plastics now make up roughly 20% of a car by weight and about 50% of a modern passenger aircraft. This is a result of significant economic benefits to these sectors, thanks to a combination of the plastics low cost, versatility, durability, and high strength-to-weight ratio. The success of plastics is reflected in the exponential growth in their production over the past half-century (Figure 2). Since the 1960s, plastics production has increased twenty-fold, reaching 310 million tonnes in 2014. Plastics production is expected to double again in 20 years and almost quadruple by 2050. Packaging is the largest application of plastic, representing *ca.* 25% of the total production volume.

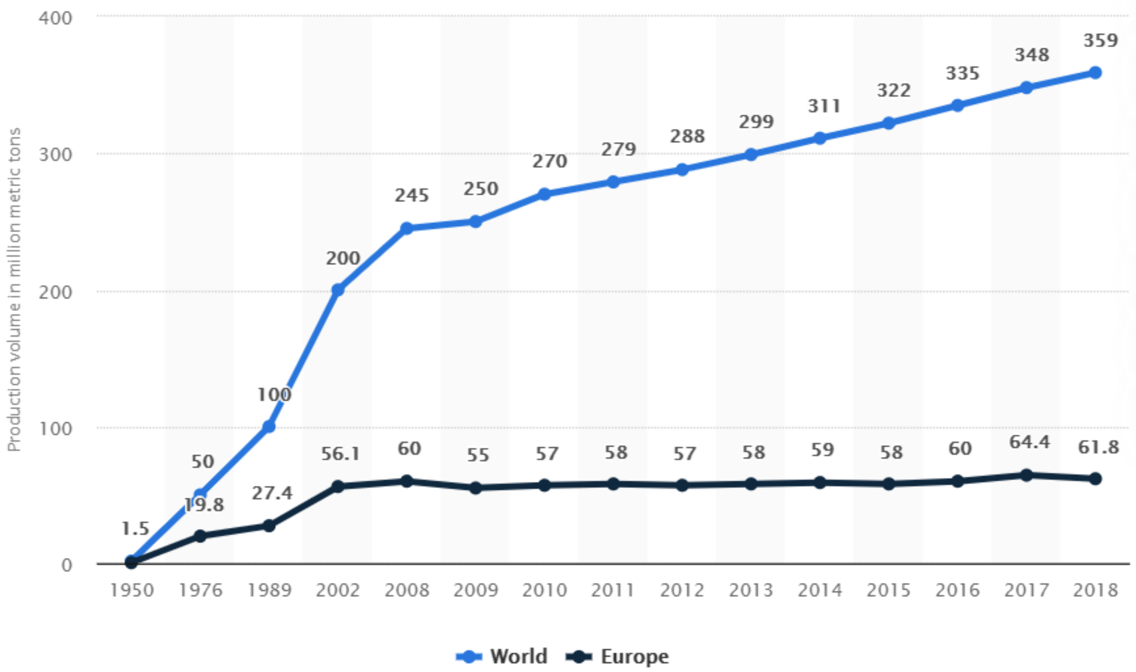


Figure 2. Growth in global plastics production during the years 1950 – 2018 (Source: Statista.com)

As packaging materials, plastics are especially inexpensive, lightweight, and high performing (Figure 3). Some aspects of plastic packaging are environmentally beneficial. Its low weight reduces fuel consumption in transportation, and its barrier properties increase the shelf life of fresh products, which reduces food waste. As a result of these characteristics, plastics are increasingly replacing other packaging materials.

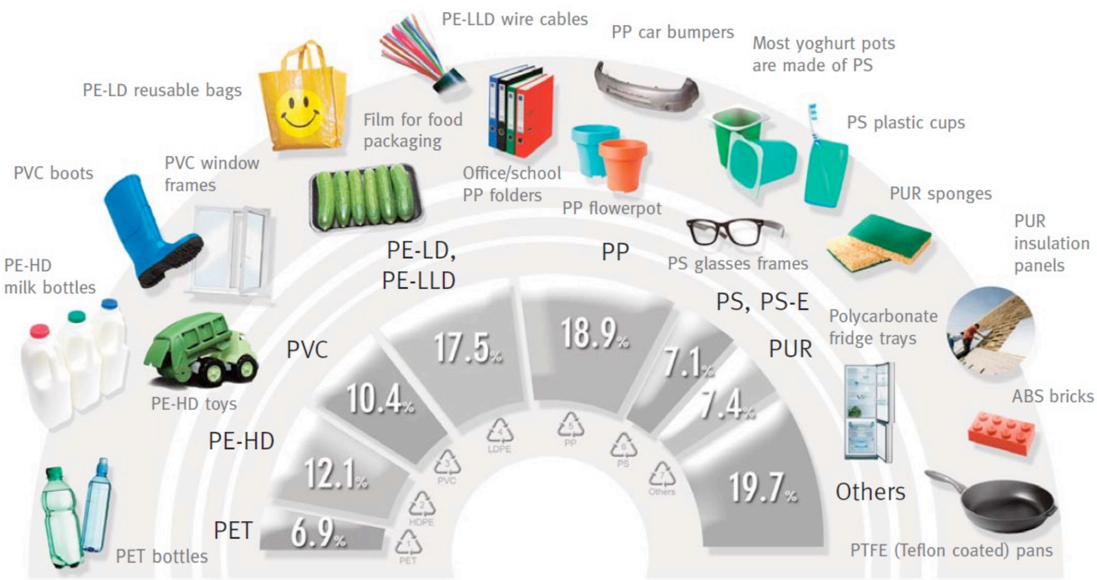


Figure 3. European plastics production by polymer type in 2013 (Source: Plastics Europe).

Chemistry and composition of plastics and the impact on recycling

Plastic typically consists of multiple components. The main component, the polymer resin, is mixed with components called **additives** to enhance their performance.[9] These may include inorganic fillers (carbon or silica) to reinforce the plastic material, thermal stabilisers to allow the plastics to be processed at high temperatures, plasticisers to render the material pliable and flexible, fire/flame retardants to discourage ignition and burning, and UV stabilizers to prevent degradation when exposed to sunlight. Dyes, matting agents, opacifiers and lustre additives might also be used to enhance the appearance of a plastic product. Additives are often the most expensive component of a formulation, and the minimum quantity needed to achieve a given level of performance is generally used. The additives are intimately mixed with the polymer or compounded into a formulation that is processed into the shape of the final product. Plastic materials that are collected after use may also include contaminants as a result of improper cleaning, staining or absorption of substances from the environment. Mixed plastic waste may contain 'legacy' materials which have been phased out of plastic production but may still exist in older plastic products.

Certain additives and monomers have already raised concerns about the risk of adverse effects on human health and the environment, for example bisphenol A (BPA) and phthalates, which are used as plasticisers in PVC and PC materials.[10-14] Additives can also cause major issues in polymer recycling, for example contaminants, legacy materials or unknown substances incorporated into recycled plastics may prohibit the re-use of recycled plastics in food packaging or in consumer goods. Additives are also a major concern for chemical recycling, which we will discuss in more detail in this article. For example, some additives may not be compatible with the pyrolysis or chemical depolymerisation processes that are used to transform polymers back to useable monomers, so their fate needs to be monitored.

The large-scale use of plastics has huge impacts on our planet and economy. Plastic materials are rarely recycled today. Almost 95% of plastic packaging material in the world, with a value or GBP 65 – 95 billion annually, is lost to the economy after a short first use (Figure 4).[15] Petroleum is consumed in their production, deepening our reliance on fossil fuels and thus driving climate change.

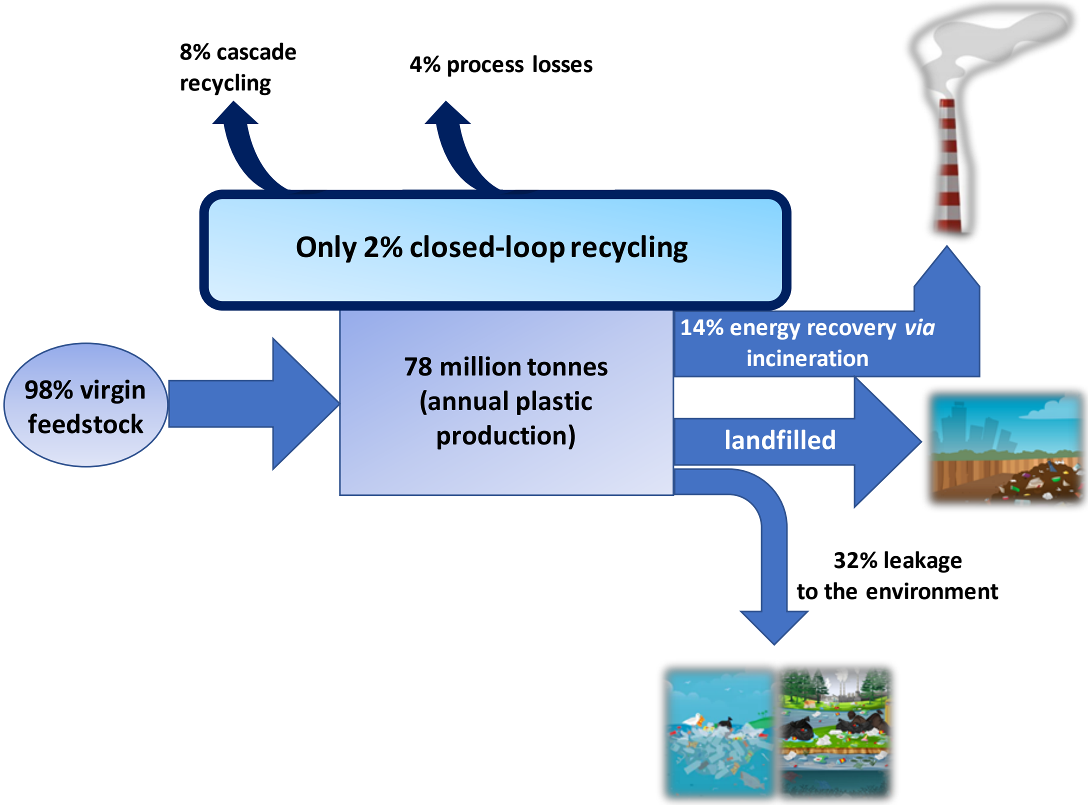


Figure 4. Global flows of plastic packaging materials in 2013.[15]

More than 40 years after the launch of the well-known recycling symbol, only 14% of plastic packaging is collected for recycling. Over 40% of the approximately 80 million tons of plastic packaging used every year is currently discarded in landfills, with 80% of this fraction escaping official collection systems, i.e. being dumped in an illegal manner,[15, 16] contributing to the pollution of ecosystems across the world with yet not fully understood implications. Another 14% is destined to be incinerated, mostly through incineration in mixed solid waste incinerators. A major concern with this methodology is that harmful pollutants generated during energy recovery processes (carbon dioxide - CO_2, sulfur dioxide - SO_2, and oxides of nitrogen - NO and NO_2 - together known as NO_x) can have negative health effects, if adequate pollution controls are not in place.[17] Even when appropriate pollution controls are in place, the resulting by-products need to be disposed of appropriately.

Collecting and sorting diverse range of single-use plastic packaging either from post-consumer or from post-industrial domains is costly and time consuming, and the obtained material variation reduces the quality of recycled plastics.[18] At present, the largest amounts of plastics that reach reprocessing are mixed plastic bottles and mixed plastics, which contains packaging based on different polymer types. The growing consumer preferences towards additive-free and fresh foods with increased shelf lives have also contributed to an increased use of mixed layer packaging (MLP) by manufacturers in recent years. These MLPs are particularly difficult to recycle because it is difficult to separate the layers. To address this issue, newly re-designed manufacturing routes to existing plastics with a focus on more benign material inputs and inherently recyclable components in the final products must be developed. Whilst a trend towards avoiding the use of MLP is observed, it is unlikely that single polymer packaging will address all packaging requirements, thus making alternative solutions for re-use or recycling of MLP an urgent need.[19, 20]

Chemical recycling of plastic materials

Physical recycling methods are designed to preserve chemical structure and physical properties of the original plastic in the recycled material. However, many mechanical recycling processes lead to property deterioration, even if care is taken during sorting and reprocessing, for example discolouration or loss of strength/toughness caused by decreases in molar mass, contamination with residues or cross-contamination with other types of polymer.[16] As a result, only rarely are post-consumer recycled plastic resins used to make the original product. Unpredictable phase separation during reprocessing mixed plastic waste stream is also an issue. The terms downcycling and cascade recycling can therefore be used to describe much of traditional mechanical recycling.

One strategy that has been gaining attention is chemical recycling, the depolymerisation or monomerisation of the polymer component, to allow the recovery of small organic molecules from plastics with deteriorated properties. The depolymerisation of polymers aims to retrieve the monomers in high purity so they can re-polymerised into polymers with the same or similar quality and functionality as in new plastic, allowing continued use in high performance plastic application.[21, 22] The term 'chemical' is used because the polymer has to undergo a chemical reaction. Partial depolymerisation to oligomers or producing mixtures of other hydrocarbon compounds through a process called pyrolysis are also approaches that are investigated; these materials may be used as an input for the production of new plastics or petrochemicals by means of heat or chemical agents.[3] Chemical recycling is attracting much attention because the material flow is cyclic, and value of the product is maintained. It will also allow fulfilment of ambitious recycling target for bottles, which cannot be met with mechanical recycling alone.

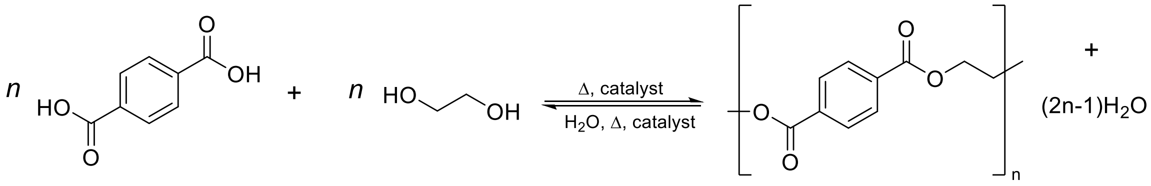
As mentioned, two major approaches to chemical recycling are pursued:

1) the inverse of the polymerisation reaction called de-polymerisation, which is usually take place in organic or aqueous liquids under optimised temperature and pressure conditions. The temperatures of this process can be fairly high, in the range of 150-200°C. This is often aided by adding a catalyst. This is process is favoured for polymers synthesized by condensation.

2) 'Pyrolysis' or thermal cracking (thermolysis) in which bulk plastics are subjected to high temperatures in the absence of oxygen.[23] This is the process of thermally degrading long chain polymers synthesized *via* an addition polymerization process into smaller, less complex molecules through heat and pressure. These plastics are mainly polyolefins (PE, PP, PS, PVC, polybutadiene, polyisoprene), acrylics (polymethacrylates, polyacrylamide polyacrylonitrile) and other vinyl types (poly(vinyl acetate), poly(vinyl acetals), poly(vinyl ethers)). The process requires intense heat with shorter duration and in absence of oxygen. The three major products fractions that are produced during pyrolysis are oil, gas, and char and each usually is comprised of a mixture of compounds.

The depolymerisation methodology can be applied to condensation polymers such as polyesters (PET, poly(butylene terephthalate), PC, PLA), polyamides (aliphatic and aromatic nylons, polyimides), formaldehyde resins (phenol–formaldehyde resins, urea–formaldehyde resins), polyurethanes (polyurethane rubbers and foams, spandex fibres) and other polymers (epoxy resins). Different reagents (nucleophiles) can be utilised leading to various forms of chemolysis (hydrolysis, glycolysis, methanolysis, aminolysis, ammonolysis). These reactions provide a wide variety of small molecules from a single plastic or polymer.

PET is the most commonly used thermoplastic from the polyester family (*ca.* 13% of world plastic production), and it is used in a large variety of applications. It is also the most recycled polymer in the world, with current industrial applications of recycled material mainly in Europe and USA. Demand for recycled PET is bound to increase, and several large-scale users of PET (*e.g.* Evian, Coca-Cola) have recently announced ambitious recycling targets. According to the European Environment Agency (EEA), the rate of PET bottle recycling reached 57% in 2017 in Europe,[1, 24] an encouraging number only clouded by the high portion of mechanical recycling, which leads to low-value materials, mainly textile fibres. Because of its abundance and high recovery rate, PET is one of the most studied polymers for depolymerisation.[2, 3, 22, 25-31] It is industrially synthesised via the poly-esterification of terephthalic acid (TPA) and ethylene glycol (EG) at high temperatures under reduced pressure in the presence of a catalyst, exploiting a standard polycondensation reaction (Scheme 1).[32] The reduces pressure is needed to remove the water and drive the reaction. The inverse of the polymerisation reaction using water as the reagent is the hydrolysis of the polyester which ultimately leads to the production of TPA and EG.



Scheme 1. PET synthesis (polycondensation) and depolymerisation (hydrolysis) routes.

It should be noted that closed-loop chemical recycling process is already in place on an industrial scale for Nylon-6, the most popular nylon grade, is a polymer synthesised from the polymerisation of caprolactam.[15, 33] PLA, another commodity bioderived plastic which is mainly used for disposable coffee cups, has been shown to degrade to smaller useful organic precursors with high yield and purity, using non-toxic organic bases as catalysts.[34] Recently, it was discovered that the organocatalysed depolymerisation of PC can be almost quantitative and can lead to the synthesis of a wide pool of useful starting materials (monomers) which can be utilised for different applications.[35]

An emerging candidate of solvents/catalysts for chemical recycling of polyesters and amides are ionic liquids (ILs).[36-38] These solvents consist of poorly coordinated ion pairs with a melting point below 100 °C and can either be protic or aprotic. They have been shown to serve as catalytically active solvents for polymer dissolution and modification, including existing and novel thermosets, compatibilisers and biopolymers such as those contained in lignocellulose.[39] Due to their ionic nature, they also have high affinity for many metal ions contained in polymerisation catalysts, for example zinc, which are liberated when plastics dissolve.[40] Other interesting and industrially attractive attributes of ionic liquids are low volatility, low flammability, and high ionic conductivity.[4, 39] Most modern ionic liquids which have been reported for the depolymerisation of PET contain various 1,3-dialkylimidazolium cations.[1] Urea or protic ILs using a strong organic base have also been reported. These are typically paired with simple inorganic/organic anions, especially chloride, acetate, and sulfonates/sulphates (Figure 5).

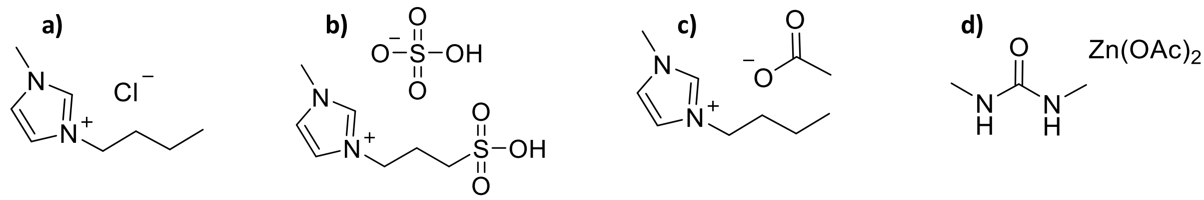


Figure 5. Ionic Liquids used for PET depolymerisation, a) [Bmim]Cl for glycolysis,[5] b) [HSO_3pmim][HSO_4] for hydrolysis,[41] c)[Bmim][OAc] for glycolysis,[42] d) 1,3-DMU/$Zn(OAc)_2$ for glycolysis.[43]

In this work, the hydrolysis of commercially available PET water bottles catalysed by low-cost and easy-to-synthesise ionic liquids was investigated. Hydrolysis was chosen as the route of depolymerisation, as TPA is a widely used monomer for the synthesis of PET and it also provides flexibility, as the co-solvent (water) is inexpensive. There is very limited information using ILs based on recent literature findings. The ionic liquids served as a catalyst and solvent at the same time, which could lead to easier solvent recovery and a high concentration of catalytic sites could lead to milder conditions during the depolymerisation reactions (relatively low temperature, T and pressure, P, and their low volatility could result in a less harmful and more environmentally friendly process compared to other methods.[44-50] The ILs selected for our study were protic, with aprotic ILs used as comparisons. Two cation types were investigated, 1-methylimidazolium, the protonated species of the simplest alkyl imidazole, 1-methylimidazole, and the positively charged conjugate acid of a strong amine base, 1,5-Diazabicyclo(4.3.0)non-5-ene (DBN).[51-55] The anions were selected to derive from well-known inorganic and organic acids, covering a range of hydrogen bonding capabilities and acidities, while aiming to generate ILs that are miscible with water. We investigated PET conversion and TPA yield after a recovery step, since these are parameters are important factors that determine economic feasibility.

Interim Results and Discussion

Synthesis and characterisation of the ionic liquids

The preparation of the protic ionic liquids was generally straightforward. A dropwise addition of the chosen acid in a temperature-regulated solution of the base in water, followed by adaptation of the water content to the desired amount. A small number of neat ionic liquids were solid at room temperature, but they became liquid after addition of water. All but one IL were water miscible. The ILs were characterised using FTIR and ^{1}H-NMR spectroscopy. Figure 6 shows FTIR spectra of [Hmim][OAc] and the base 1-methylimidazole. Formation of an IL is evidenced by the appearance of a broad peak caused by an N-H amine stretching vibration at and a peak for the carbonyl stretching in the acetate anion.

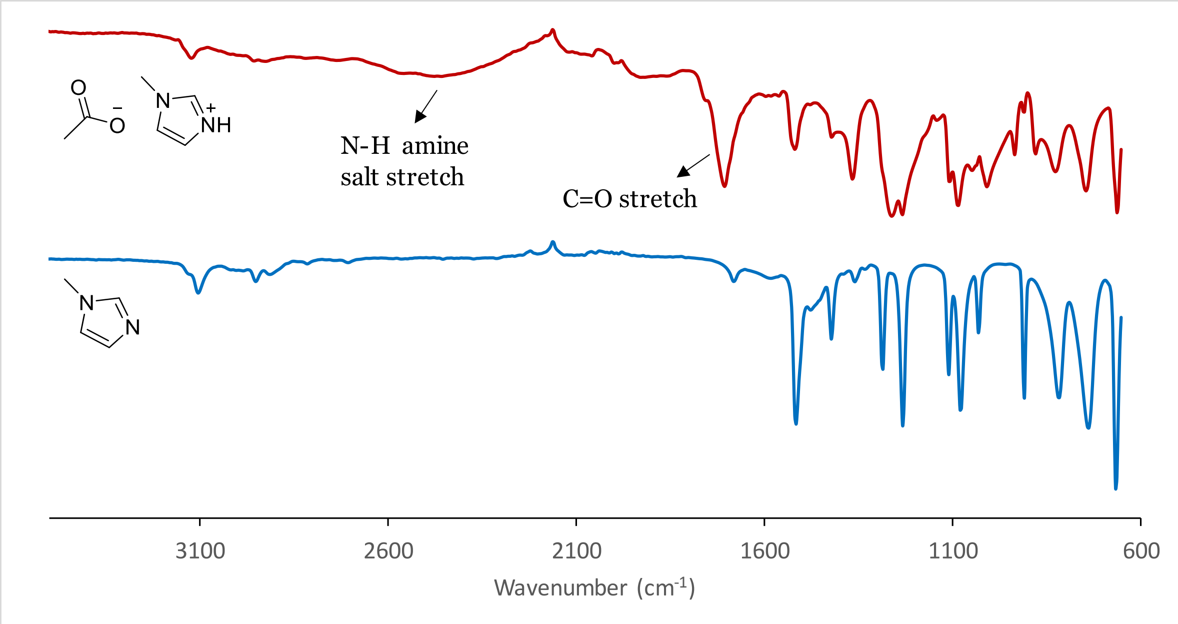


Figure 6. FTIR spectra of A) 1-methylimidazole and B) [Hmim][OAc].

The NMR spectra also showed that the proton had transferred from the acid onto the base, an example is shown in Figure 7.

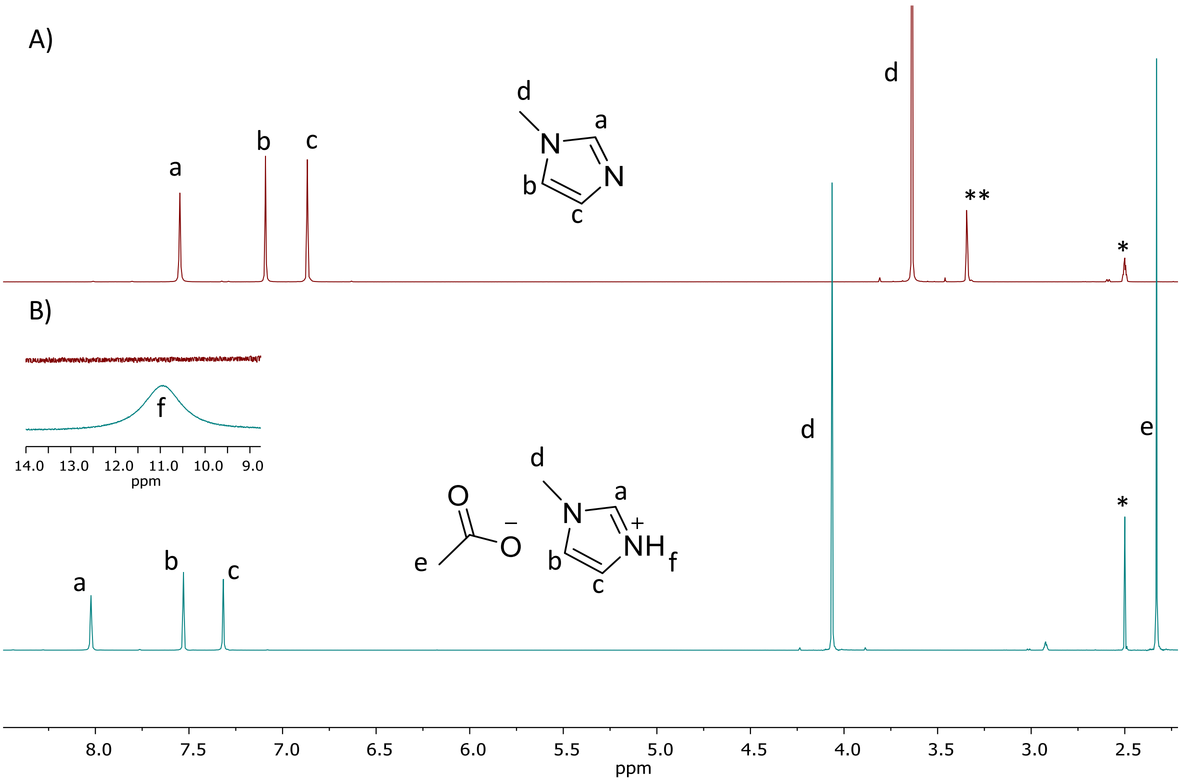


Figure 7. [1]H NMR spectra of A) 1-methylimidazole and B) [Hmim][OAc]; *(*d^6-dmso, **residual H_2O).*

Solubility of TPA in the ionic liquid water mixtures

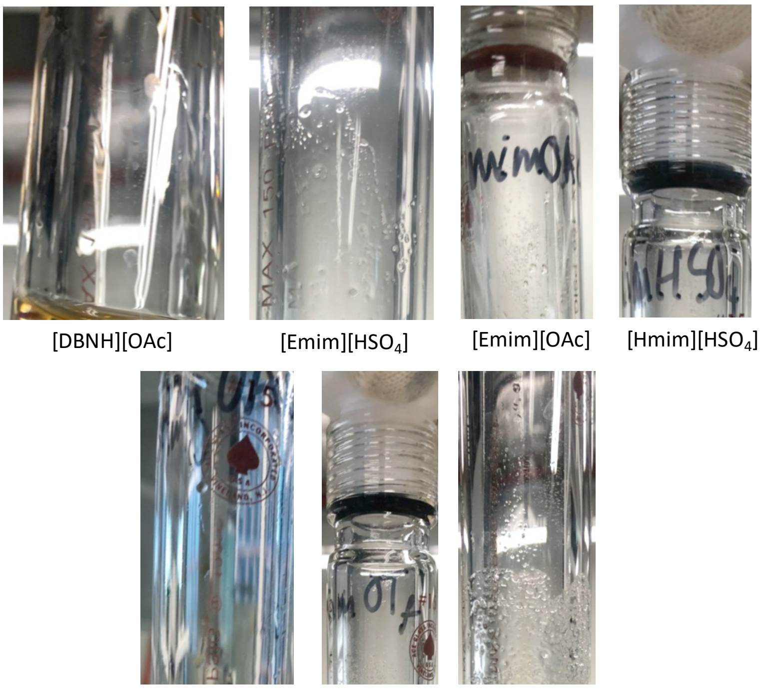
The solubility of the monomer in the medium is an important factor for chemical depolymerisation of PET to TPA. When designing the study, we assumed that monomer solubility is key to achieving high conversion, while polymer solubility is not essential. This is different to some studies which have sought out ILs with high polymer solubility.[56] Although dissolving the starting material accelerates reactions, is not necessary to achieve high conversion and product yield. All ILs were screened for their capacity to solubilise terephthalic acid (Table 1, Figure 8). As hydrolysis was the main objective of this work, water was present, and the experimental conditions of the solubility screening were identical to those used for the hydrolysis reaction. The solubility of the monomer was visually evaluated after stopping the experiments as well as after cooling the solutions to room temperature, which allowed us to evaluate the temperature dependence of TPA solubility. Solubility of ethylene glycol, the base (DBN, 1-methylimidazole) and acetic acid were investigated to provide comparisons. We also tested a range of aprotic imidazolium ILs for comparison. TPA was solubilised quite efficiently in the bases, both at the reaction temperature and at room temperature. It was expected that TPA was insoluble in water and acetic acid. For the [Hmim] ILs, TPA solubility was observed for the three ionic liquids at the reaction temperature. The only example of complete solubility after cooling the solution to room temperature was observed for 1-methylimidazolium acetate, [Hmim][OAc]. [Hmim]Cl fully solubilised TPA at the reaction temperature, but after cooling, the monomer precipitated out of solution. Temperature dependent precipitation could be used for easy recovery of the produced monomer, as it could be precipitated after conversion without any additives. In the case of [Hmim][$MeSO_3$], only partial solubility was recorded even at the high temperature. Three ILs failed to solubilise TPA.

Table 1. Solubility of TPA in the selected ionic liquids.

Entry	Medium	Soluble at reaction temperature	Soluble at RT
1	H_2O	No	No
2	EG	No	No
3	DBN	Yes	Yes
4	1-methylimidazole	Yes	Yes
5	Acetic acid	No	No
6	[Hmim][HSO_4]	No	No
7	[Hmim][$MeSO_3$]	Partial	No
8	[Hmim][OTf]	No	No
9	[Hmim][OAc]	Yes	Yes
10	[Hmim]Cl	Yes	No
11	[Hmim][$ZnCl_3$]	No	No
12	[Hmim][OAc] (2:1)	Yes	Yes
13	[Hmim][OAc] (1:2)	Yes	Yes
14	[DBNH][OAc]	Yes	Yes
15	[DBNH][HSO_4]	No	No
16	[DBNH][$MeSO_3$]	Yes	Yes
17	[DBNH]Cl	Partial	No
18	[DBNH][OAc] (2:1)	Yes	Yes
19	[DBNH[OAc] (1:2)	Yes	Yes
20	[Emim][HSO_4][c]	No	No
21	[Emim][OAc][c]	Yes	Yes
22	[Bmim][$MeSO_3$][c]	No	No
23	[Bmim]Cl[c]	Partial[b]	No

[a]visual inspection, [b]partially soluble, [c]commercial IL

Moving on to the DBN-based ionic liquids (entries 14-19), only the hydrogen sulfate IL failed to solubilise TPA, while the acetates (symmetric and asymmetric) and methane sulfonate were good solvents. Partial TPA solubilisation could be observed for [DBNH]Cl, which was further reduced upon lowering the temperature. Furthermore, four aprotic ILs were tested (20-23), which were analogues of the protic imidazolium ILs used in this work. Only [Emim][OAc] solubilised the TPA monomer, suggesting that acetate ILs are generally good solvents for TPA.



[DBNH][OAc] [Emim][HSO_4] [Emim][OAc] [Hmim][HSO_4]

[Hmim][OAc] [Hmim][OTf] [Hmim][$ZnCl_3$]

Figure 8. Representative photos of TPA solubility tests with synthesised and commercially available ILs. The non-dissolved TPA in the form of white powder can be distinguished.

PET hydrolysis with ionic liquids

PET is a thermally stable semi-crystalline plastic with a melting temperature around 250 °C, therefore the depolymerisation reactions need to be conducted at a relatively high temperature to assist with its softening. Initially, we carried out control experiments using pure base and pure acetic acid as solvents were performed, to be able to compare the performance of protic ILs (Table 2, entries 1-3). Reaction in the neat base led to near-quantitative PET conversion. Acetic acid displayed minimal catalytic activity (0% PET conversion) on its own.

Interestingly, the ability of the methylimidazolium ILs to depolymerise PET followed the same trend as their ability to solubilise TPA (Table 2, entries 4-11), so chloride and acetate ILs were able to convert PET, while conversion was not observed in the hydrogen sulfate, methanesulfonate, triflate and zinc chloride ILs. The [Hmim]Cl achieved partial conversion, while [Hmim][OAc] proved to be powerful catalytic solvent, driving the reaction to complete conversion. The resulting solution had a dark amber colour (Figure 9).

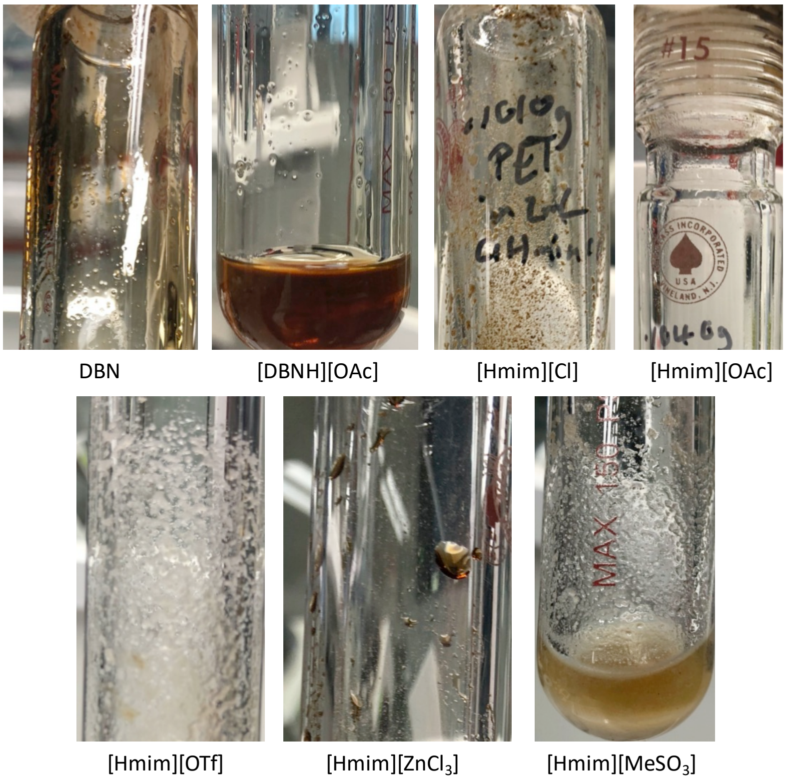


Figure 9. Depolymerisation crude solutions immediately before working-up.

Table 2. PET Hydrolysis results.

Entry	Catalyst	%PET conv.	TPA yield (%)
1	DBN	High	None
2	1-Methylimidazole	High	None
3	Acetic acid	Low	None
4	[Hmim][HSO$_4$]	Low	None
5	[Hmim][MeSO$_3$]	Low	None
6	[Hmim][OTf]	Low	None
7	[Hmim][ZnCl$_3$]	Low	None
8	[Hmim]Cl	Moderate	Low
9	[Hmim][OAc]	High	High
10	[Hmim][OAc] (2:1)	High	High
11	[Hmim][OAc] (1:2)	High	High
12	[DBNH]Cl	Moderate	Low
13	[DBNH][HSO$_4$]	None	None
14	[DBNH][MeSO$_3$]	None	None
15	[DBNH][OAc]	High	High
16	[DBNH][OAc] (2:1)	High	None
17	[DBNH[OAc] (1:2)	High	Moderate
18	[Emim][HSO$_4$][c]	Low	None
19	[Emim][OAc][c]	High	High
20	[Bmim][MeSO$_3$][c]	Moderate	Low
21	[Bmim]Cl[c]	Low	Low

[a]visual inspection, [b]partially soluble, [c]commercially available; experimental conditions: 180 °C, 3 hours, pressurised tubes. 0.1g PET, 2.0g of catalyst/solvent containing ~ 15% H_2O w/w.

Terephthalic acid isolation

Initial experiments showed that we needed to decrease the pH of the solution to recover the TPA. The isolates were washed with water and filtered, producing off-white solids (Figure 12). We confirmed with ^{1}H-NMR spectroscopy the identity of the product. The IL based on the DBN (Table 2, entries 12-17) displayed behaviour similar to the imidazolium ILs. Both acetate PILs achieved high conversion, but the isolated TPA yield low. This could be due to DBN being a stronger base (pK_a = 12.7 (DBNH) *vs* pK_a = 7.0 (Hmim)).

The amount of isolated product was high in the case of [Hmim][OAc] and [DBNH][OAc]. [Hmim]Cl and [DBNH]Cl resulted in some conversion, but low TPA yield. The ILs with the other anions were unsuccessful in converting PET. Looking at the four aprotic ILs, [Emim][OAc] (Table 2, entry 19) showed the best catalytic performance, comparable to [DBNH][OAc] and [Hmim][OAc]. [Bmim][$MeSO_3$] and [Bmim]Cl resulted in limited PET conversion and low TPA yield. [Emim][HSO_4] exhibited the weakest performance, with low PET conversion and no TPA recovery.

Characterization of recovered product

To confirm the identity of the main product, FT-IR spectroscopy was employed. The recovered TPA monomers were of relatively high purity when compared to commercially available samples (purity > 99.8%) (Figure 10).

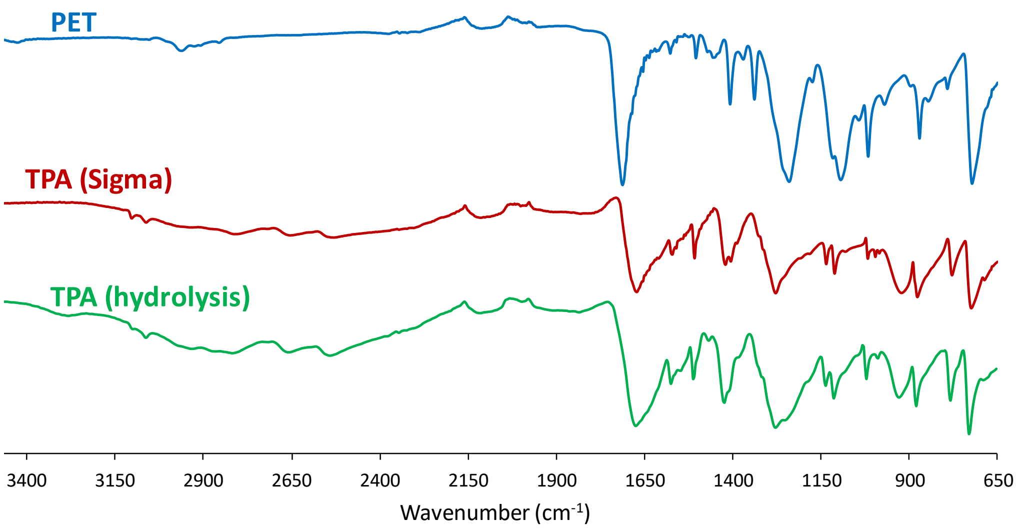


Figure 10. Stacked FT-IR spectra of a PET flake (blue), a commercially available TPA sample (red) and TPA recovered from the depolymerisation of PET catalysed by [Hmim][OAc] (green).

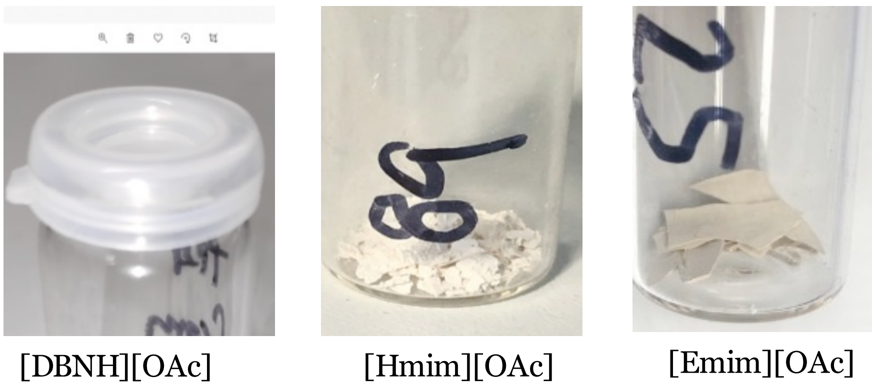


Figure 11. Photos of TPA recovered from different ionic liquids during the hydrolysis of PET.

The FT-IR spectrum of the isolated product (green line) was compared to commercially available TPA (red line). It can be seen that the product and TPA the spectra look almost identical, while the spectrum of PET is different.

Conclusion

In this study, the chemical recycling of one of the most prominent plastics in the world, PET, was attempted using low-cost and easy-to-synthesise protic ionic liquids. The motivation for the selection of these catalytic solvents are their relatively low cost, and in the potential to design them for the application. Hydrolysis was chosen as the depolymerisation strategy, as TPA is a much sought-after monomer for recycled PET. Two bases were combined with a range of organic and inorganic acids to produce protic ionic liquids. Analogous aprotic ionic liquids were used as comparisons. Among the ionic liquids examined, the ILs with acetate anion were the best solvents for PET conversion, and high TPA yield after acidification was achieved. Further studies into the stability of ILs is being carried out, and monomer recovery is also subject of on-going investigation. In summary, our study shows that there is potential for low cost ionic liquids to be used in chemical recycling of polyester plastics.

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Sustainable Hospitals – Recycling Healthcare Plastics

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Healthcare relies on single-use plastics for sterility and the materials properties they exhibit. Many of these plastics are present as composite materials, with other polymers, thin layers of metals or both. The Sustainable Hospitals project within "Rethinking Resources and Recycling – RE3" is mapping the flow of plastic materials throughout hospital and healthcare environments in partnership with NHS England and looking at chemical and catalytic solutions for separating and valorising unavoidable plastic waste.

Introduction

Single-use plastics are ubiquitous throughout our everyday lives and the environmental impacts of their production and disposal have become a common topic in public discourse over recent years. An increased prevalence of campaigns to encourage consumers to avoid single-use plastics such as drinking straws and disposable coffee cups has further highlighted the issue. Less familiar to the public is the use of single-use plastics in hospitals, a setting in which decisions regarding the types of materials employed during medical procedures go beyond the scope of individual buying power and as such often escape the public's gaze.

Healthcare applications represent a very specific use case for disposable items made of polymers or composite materials that contain polymeric components. Effective materials will generally have been through extensive trials, especially in the case of medical devices that are in direct contact with patients, medicine, or contaminated waste. Substitution or reuse could increase the threat to patients and healthcare workers alike or require prohibitively expensive and lengthy trials to identify replacements – several years even in best case scenarios.

For these reasons, the 'reduce, reuse, recycle' approach is hard to apply to healthcare plastics, particularly in light of COVID19 and the increased risk of contamination, and we must look at solutions lower down in the waste hierarchy (Figure 1), i.e. material recycling. The case study on mapping of material flow presented herein considers the applicability of this strategy.

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On a global scale, waste management strategies in hospitals are diverse and regulations differ between geographical regions. For instance, in the UK, the National Health Service (NHS) actively considers the Waste Hierarchy when developing waste management strategies, whereas in some countries there are no guidelines in place for waste separation, classification or disposal.[1]

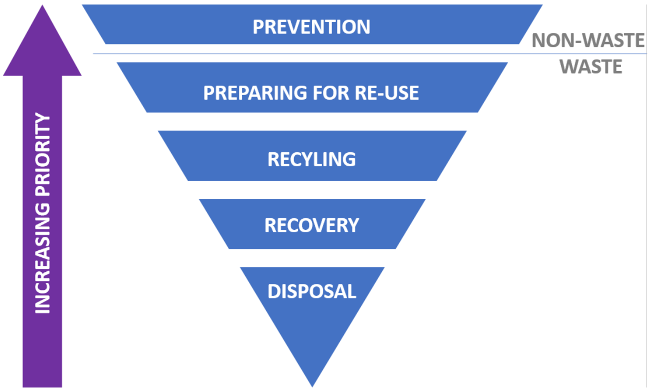

Figure 1. European Commission (2008) DIRECTIVE 2008/98/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 November 2008 on waste and repealing certain Directives. European Commission. Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0098

The first aim of the project was to identify waste streams and how these streams are dealt with in hospitals, as covered by peer-reviewed studies in scientific journals. This review answered three research questions: 1) What are the waste plastics generated by hospitals (including types, functions and amounts)? 2) What are the current waste management strategies for these waste steams? 3) What alternative waste management strategies have been explored and implemented by the hospitals?

The waste hierarchy has been recognised internationally as a tool to promote progressive waste management. Indicating an order of preference for the reduction and management of wastes, the waste hierarchy prioritises waste prevention, followed by (preparing for) re-use, recycling, recovery and, as a last option, disposal.[1]

The review intentionally included case studies from a range of countries and international contexts, to draw comparisons with, and lessons for, hospitals' practices in the UK. Various plastics are used in hospital settings and established mechanical recycling processes for polymers can be applied to several common plastics, provided pure and uncontaminated feeds are available.

Research at the University of Manchester has demonstrated that materials, such as mixed plastic, previously thought to be 'unrecyclable', can be chemically recycled.[2] For 'difficult' materials identified by the material flow methodology proposed herein, where polymers with recycling potential are composite components, or unacceptably contaminated, an alternative strategy will be considered. The diversity of such items and their quantities are shown in Table 1. We present the example of a single-use medicine blisterpack, comprised of a polyvinylchloride/ aluminium/ polyamide laminate. This material is likely to be contaminated, and the regulatory barriers to its replacement demand a more urgent solution to this existing waste burden. Further work will also consider intravenous fluid (IV) bags that are multi-component and multiple-polymer laminates for barrier protection, ease of printing on external surfaces. Again, this is a use-case with heavy restrictions on re-use, replacement materials and end-of-life contamination. A key goal of this project being separation of composites to prepare them for further processing, either mechanical or chemical recycling

Table 1 – Disposable plastic products that passed through NHS Supply Chain in 2014/2015, ranked by tonne per annum and percentage of total plastic waste produced. Data provided by NHS Sustainable Development Unit.

Product group containing plastics	**Use (te p.a.)**	**%**
Single Use Theatre Protective Clothing (inc drapes)	9,402	13
Examination Gloves	7,952	11
Disposable Wipes and Cleaning Cloth products	7,045	10
Catering Products Tableware and Light Equipment	5,628	8
Polymer Products (aprons and bags)	5,244	7
Medical Hollowware	5,044	7
Disposable Continence Care products	5,029	7
Blood Collection Systems(sample tubes & syringes)	4,851	7
General Woundcare	4,066	6
Suction Consumables (catheters, tubing, drains)	3,823	5
Syringes, Needles And Associated Products	3,353	5
Clinical Waste Containers	3,216	4
Medical Packs And Sterile Supplemental Products	3,028	4
Needlefree Connection Systems Products	2,324	3
Urology Products (Drainage bags, catheters)	2,296	3
TOTAL Disposable Plastic containing Products	**72,301**	

To quantify the potential benefits of recycling healthcare plastics it is necessary to investigate the environmental sustainability of proposed waste treatment methods. Life cycle assessment (LCA) is widely utilised to evaluate the environmental impacts of processes and products over their entire life cycle.[3] This analysis is crucial to determining the main sources of impacts of a proposed process or product, allowing modifications in early design stages and supporting sustainability-oriented decision-making. However, novel technologies often rely on complex reagents (e.g. ionic liquids) unsupported by commercial LCA databases.[4] Therefore, LCA practitioners must generate the necessary inventory data for the production of materials and operation of processes unavailable in LCA databases to assess such complex systems. Moreover, LCA practitioners need to follow suitable scaling-up protocols[5] to determine the potential impacts of designed technologies at industrial scale, allowing direct comparison to commercially-available technological options.

This article seeks to redefine healthcare plastics as a potential resource and to assess the environmental sustainability of separating layered materials (e.g. blisterpacks) into their basic components (e.g. PVC, aluminium, polyamide nylon). Ionic liquids are used for this purpose, allowing the recovery of the constituent materials and their reutilisation. This innovative approach is contrary to the incineration policy that is typically employed by the NHS and other health providers. It has been demonstrated, via voluntary producer responsibility schemes like RecoMed, that recyclable polymers exist in the clinical setting, and that their value can be reclaimed after use. Some plastics simply cannot be eliminated from the day-to-day running of hospitals and trusts, but there are initiatives needed around separation of complex materials that would allow identification of recyclable plastics as well as around the redesign of products that would facilitate recycling.

Methods

Material Flow Mapping

The review of literature on waste management strategies in hospitals used the waste hierarchy and technology readiness levels (TRLs) as a framework for analysis.

Experimental Case Study

Formpack blisterpack material was supplied as laminated sheets by AstraZeneca. Trihexyl(tetradecyl)phosphonium chloride ($[P_{14,6,6,6}]Cl$, purity ≥95 %), and trihexyl(tetradecyl)phosphonium tetrafluoroborate ($[P_{14,6,6,6}][BF_4]$, purity ≥95 %), were purchased from Cytec Industries Inc. Trihexyl(tetradecyl)phosphonium diethylphosphate ($[P_{14,6,6,6}][(EtO)_2PO_2]$, purity ≥95 %) was purchased from Merck. Trihexyl(tetradecyl)phosphonium acetate, $[P_{14,6,6,6}][AcO]$, and trihexyl(tetradecyl)phosphonium bis(trifluoromethane)sulfonimide, $[P_{14,6,6,6}][NTf_2]$, were synthesised following previously published procedures.[6]

To perform dehydrochlorination, 0.20 g of blisterpack squares were added to 5 g of IL and heated at a constant temperature (90 °C) for 24 hr whilst stirring at 300 rpm. After the reaction, the remaining solid was separated from the IL, and washed with ethanol 3 times in an ultrasonic cleaning bath for 5 min to minimise IL residue on the material. Thereafter, the samples were dried at 50 °C for at least 24 h.

Life Cycle Assessment (LCA)

The life cycle environmental impacts of the blisterpack separation process using $[P_{14,6,6,6}][Cl]$, $[P_{14,6,6,6}][Br]$ and $[P_{14,6,6,6}][HexO]$, were assessed via LCA, in accordance with the ISO 14044 guidelines.[7] The study was from 'cradle-to-gate' (Figure 2) and included the production of the ionic liquids and the process for material recycling of blisterpacks.

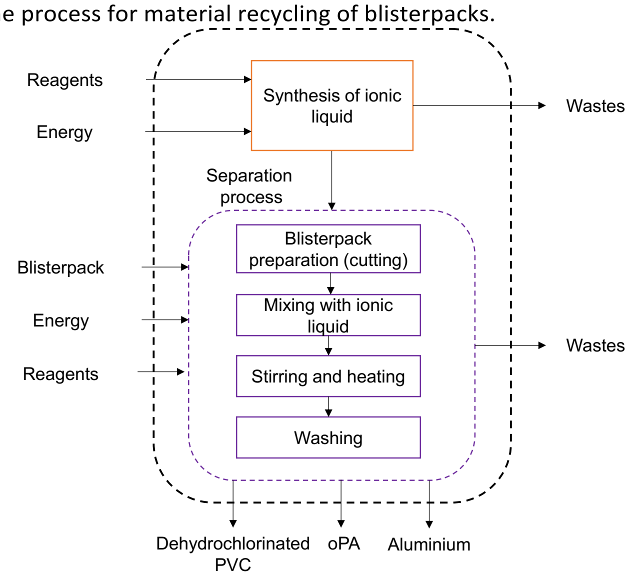

Figure 2. Blisterpack separation process using ionic liquids and system boundaries considered in the LCA study.

Inventory data for the LCA were obtained from the experimental data (e.g. amount of reagent, temperature, reaction time, products) on the separation of blisterpacks and dehydrochlorination of PVC.

The production of the ionic liquids was modelled according to the procedure described in the methodology section. The synthesis route for each ionic liquid was organised in "life cycle trees". Figure 3 reports the life cycle tree of $[P_{14,6,6,6}][HexO]$. This example was selected to show that the synthesis of ionic liquids can be complex, and it might require the use of other ionic liquids (e.g. $[P_{14,6,6,6}][Cl]$) as precursors.

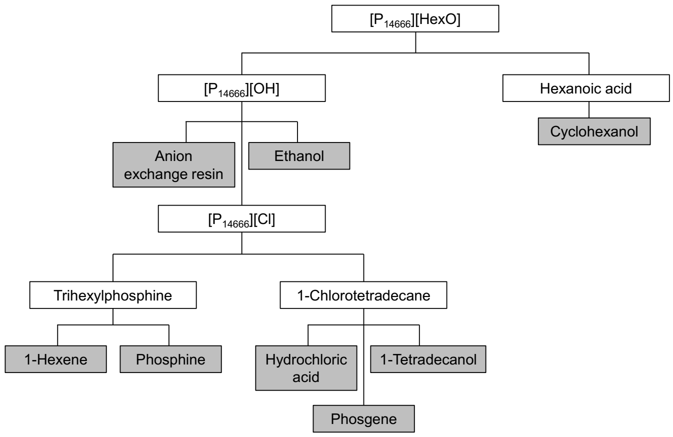

Figure 3. Life cycle tree describing the synthesis steps of $[P_{14,6,6,6}][HexO]$. Chemical compounds reported in grey boxes are available in Ecoinvent database.[8] $[P_{14,6,6,6}][HexO]$: trihexyl(tetradecyl)phosphonium hexanoate; $[P_{14,6,6,6}][Cl]$: trihexyl(tetradecyl)phosphonium chloride; $[P_{14,6,6,6}][OH]$: trihexyl(tetradecyl)phosphonium hydroxide.

Background data were sourced from the Ecoinvent database v3.6 [8]. The environmental impacts were estimated using the ReCiPe 2016 V1.1 impact assessment method at the mid-point level, following the hierarchist approach. [9]

Results and Discussion

Material Flow Mapping

A key advocate of the waste hierarchy has been the European Union, which formally adopted this tool within Waste Framework Directive (2008/98/EC) and has since been driving member states to significantly improve their waste management practices.[9] However, the use of the waste hierarchy within EU waste policy has been criticised for a continual emphasis on low priority strategies, an absence of targets related to waste prevention and the lack of nuance concerning the maintenance of value in material recovery. For example, wastes that are up-cycled, through multiple life cycles, are valued the same as waste materials that are down-cycled and, thus, only achieve one extra life cycle.

While application of the waste hierarchy can determine the preferred waste strategy, access to (and the maturity of) available technologies will often determine the strategy employed. To determine if a technology is ready for employment and to support development, Technological Readiness Levels (TRLs) can be utilised. Generally, there are nine TRLs, which can be grouped into six activities: basic technology research (TRL 1-2), feasibility studies (TRL 2-4), technology development (TRL 3-6), technology demonstration (TRL 5-7), development and demonstration of systems and subsystems (TRL 6-9) and system test, launch and operations (TRL 8-9). In waste management, TRLs have been combined with the waste hierarchy to present a framework that enables technologies to be assessed both in terms of maturity and contribution to progressive waste management.

Where studies were clear on the specific types of plastics used, the review has identified the following types of plastics commonly explored in the literature: polypropylene, polyethylene, PVC, and plastic films for packaging, as well as other materials and additives, such as aluminium, titanium, iron, and even mercury compounds. HDPE and LDPE only appeared in one study.[10] The most frequently mentioned products where these plastics appeared in the hospital context included packaging, blue wrap, syringes and bottles. Around 15% of the reviewed literature researched blister packs and IV bags. Many studies did not specify the product at all and referred to hospitals' entire plastic waste stream in general.
Geographically, the focus of the studies was dominated by examples from developed countries, mainly from North America and Europe. The main examples from developing countries covered hospitals in South Asia and Middle East. The latter regions predominantly relied on incineration and sanitary landfilling for managing their hospital waste, although there was also an example of uncontrolled landfilling.[11] In developed regions, while incineration and sanitary landfilling were common, recycling was present as an option in at least half of the studies.

Among alternative waste management strategies trialled in developed countries, the main options were waste reduction and segregation, and one study explicitly mentioned chemical recycling.[12] Studies on developing countries named recycling, microbial remediation and gasification as alternative waste management strategies. Note that 'alternative' does not necessarily mean innovative; rather it is a waste management strategy new to a particular context. The majority of the strategies involved mature technologies at the high TRL levels. As an illustration of returning to some of the old practices common in the 20th century, some alternative strategies currently arising in both developed and developing countries included reuse with sterilisation.

In the UK context, the NHS is legally required to consider the waste hierarchy when applying waste management strategies. NHS trusts categorise all wastes into three groups (Infectious, Offensive and Municipal) based on the potential risk of infection. Wastes categorised as offensive and municipal, such as gloves, aprons and catering products, can be recycled where existing local waste treatment facilities are utilised. However, depending on local waste infrastructure and requiring the presentation of non-contaminated waste streams, often NHS waste is sent for incineration or disposed of via landfill.[13]

Gaps in research, based on this review of literature, are mainly related to the lack of specificity when discussing hospital waste streams and its constituents: many studies did not name the specific materials and additives, even though they often require tailored waste management strategies. Another noticeable gap was in how little innovation seemed to be present in both the current and alternative waste management strategies deployed in hospitals (unless it is an issue of under-reporting such innovative practices by the literature).

Experimental Case Study

Knowledge of technical product specifications aids in overcoming recycling challenges and helps to redesign materials. We demonstrate that ionic liquids facilitate separation of the three layers in blisterpacks (e.g. orientated polyamide, aluminium and PVC) shown in Figure 4, and through the simultaneous dehydrochlorination of the PVC, allowing its inclusion in chemical recycling with other polyolefins steams identified in NHS waste.

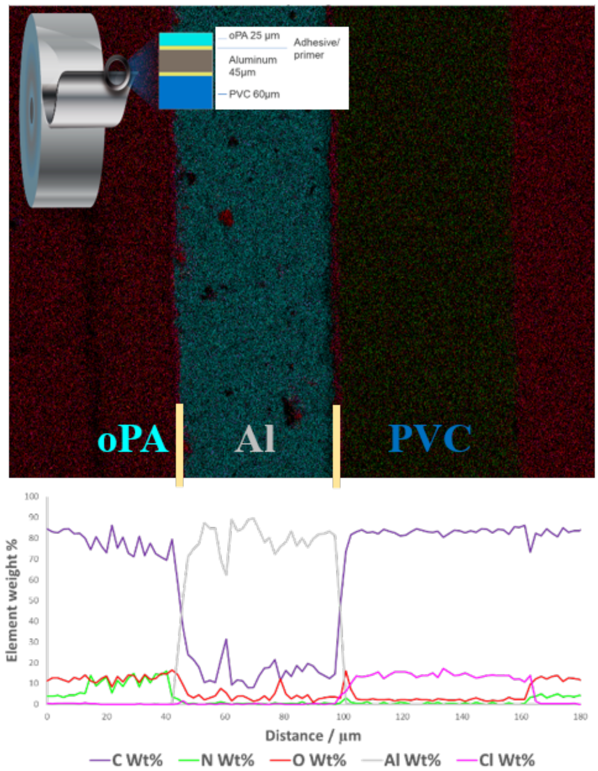

Figure 4. The structure of the blisterpack is demonstrated in cross section, accompanied by elemental analysis of the layers.

A range of phosphonium ionic liquids demonstrates the ability to delaminate and separate the blisterpack layers. Selection of an appropriate ionic liquid also enables the removal of chlorine from the PVC component. Chlorine is a problematic element in plastic pyrolysis (thermal decomposition in an oxygen-free, inert environment) as it can cause corrosion, and in catalytic hydrocracking technologies, where it can damage the catalyst. These processes create valuable chemical feedstocks from waste polymer but are sensitive to the feedstock. Dehydrochlorinated PVC could be included in a mixed plastic feed for these liquification processes and is more likely to be tolerated than untreated PVC. This applies to various pyrolysis, gasification, and catalytic degradation processes

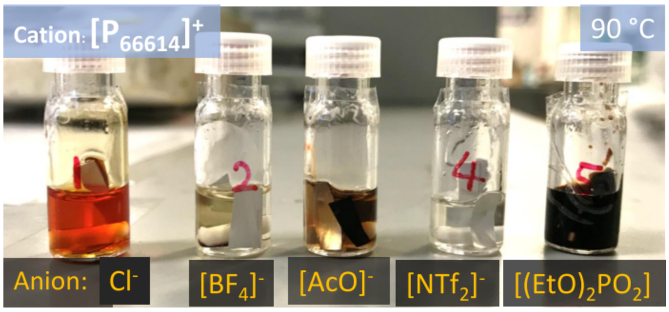

Figure 5. Even at low temperatures of 90°C, a blisterpack can be deconstructed into its components by ionic liquid catalysis. The colour of the liquid represents the level of PVC dehydrochlorination that has occurred.

Figure 5 demonstrates the importance of the anion type when selecting an ionic liquid, as this property is key in targeting the level of dehydrochlorination that the process can achieve. Ongoing research will assess the potential of dehydrochlorinated PVC to be included in catalytic hydrocracking of waste plastic. Multicomponent IV bags will also be included, and due to their similarity with previously assessed post-consumer plastic feedstocks,[14] it is anticipated that they will be an appropriate feed for the process.

Life Cycle Assessment

The life cycle impacts estimated for the separation process utilising $[P_{14,6,6,6}][HexO]$ are shown in Figure 6. It can be seen that the impacts are mainly related to the use of ionic liquids (57-91% contribution), as the process only requires the use of ionic liquids and ethanol and is carried out at mild temperatures. Note that the impacts of ionic liquids depend on their synthesis route and precursors utilised for their production.[15] This is because ionic liquids differ in the amounts of reagents and energy consumed by the process and in the amounts of wastes produced. The waste management strategy considered the incineration of produced organic wastes. Thus, wastes contribute 43% to the impact on climate change and show relevant contributions in the other categories considered (up to 13%). Therefore, the environmental impacts of the proposed waste treatment method can be reduced by reducing the amount of ionic liquid utilised. Moreover, simpler synthesis routes, which rely on more sustainable reagents and possibly, allow reducing the amount of waste produced could also reduce impacts related to the use of ionic liquids.

As discussed, treatment with ionic liquids allows separation of the layered structure of a blisterpack. Three potentially valuable products, dehydrochlorinated PVC, oPA and aluminium, are produced. However, this study focussed on the separation of blisterpack layers utilising ionic liquids. The fate of produced materials has not been investigated further. Nonetheless, if allowed by relevant regulation, these materials could be further processed and recycled (e.g. hydrocracking, aluminium recycling), potentially increasing the benefits of the process. Additional studies, aimed at investigating suitable recycling processes for produced aluminium, dehydrochlorinated PVC and oPA are necessary. Those experimental results could be utilised to model a recycling process for blisterpacks, which would allow quantifying benefits and drawbacks of the proposed waste treatment method.

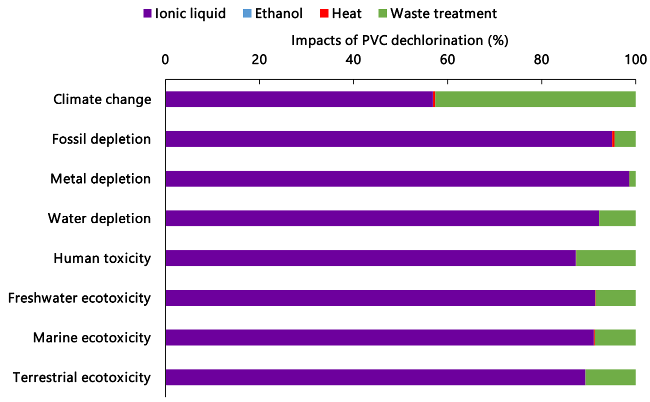

Figure 6. Contribution of different life cycle stages to environmental impacts of the separation process utilising trihexyl(tetradecyl)phosphonium hexanoate.

Conclusions

The sustainability of single-use plastic, particularly in a healthcare setting, requires the entire value chain to be considered from cradle to grave. Creating a carbon cycle within this that will include anthropogenic carbon sources, such as plastics, is vital for reducing the burden on plastics production and waste on the environment. A combined approach that considers how waste flows through large systems is important for the identification of the best intervention strategies.

In this work, we presented a case study of a 'difficult' single-use plastic that is amenable to recycling, that would otherwise simply be disposed of. Bringing healthcare plastic outputs up the waste hierarchy will be a great challenge, and there is no single great solution, but via a multi-faceted approach, significant sustainability improvements can be made.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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Waste Plastics in Clinical Environments: A Multi-disciplinary Challenge

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Single Use Plastics are an essential and invaluable component of modern, safe and effective medical and dental care. They are used in the manufacturing of complex compound products, devices and their associated packaging. The volumes used are in the thousands of tones/year and to date, the vast majority of this ends its single-use life as waste in landfill sites or incineration, thus following a very wasteful linear economy. This multi-disciplinary project has established baseline data of stakeholder behaviour, usage and waste management through innovative recycling technologies. We have confirmed that reducing and recycling on an impactful scale can only be achieved through a highly collaborative and multidisciplinary approach to understand, engage and influence behaviour changes at each stakeholder point of the supply chain, thus reverting to a more environmentally sustainable circular economy.

Introduction

Polymers exhibit a range of properties that make them invaluable in clinical settings. These materials may be assembled in a wide range of combinations, including compound multi-layered structures and highly specific complex shapes, to create a clinical item or packaging with optimised properties. The low cost of raw materials and bulk fabrication means that a wide variety of single-use products may be manufactured at exceptionally low costs. The combined manufacturing versatility, cleanliness/sterility guarantee and cost effectiveness of these plastic devices makes reusing and/or recycling economically unattractive, with disposal being the more likely solution. In this way, a highly wasteful linear economy for Single Use Plastics (SUPs) is created. SUP devices, products and packaging have become a ubiquitous component for the provision of safe and economical healthcare as they fulfil the needs of every stakeholder in the supply chain, whilst at the same time providing the required clinical and public confidence of using a new clean and/or sterile device every time with zero risk of contagion. In this manner, SUPs fulfil all the major requirements of a risk-averse industry that operates within very tight budgetary constraints.

Medical and dental clinics consequently generate substantial volumes of waste plastics, although precise data on the amount and composition is often lacking (1,2). These healthcare settings include operating theatres, dental surgeries, wards, and pharmacies utilise a wide range of disposable plastics in varied applications including personal protective equipment (PPE), single use devices, instruments, and packaging. The volume of plastic packaging alone discarded by the healthcare sector in the UK is staggering; with over 590,000 tonnes generated annually, more than the entire municipal waste output of Luxembourg (England Chief Medical Officer Report 2016-17). Almost all waste plastic from clinical environments is directed to landfill or incineration. The cost to the NHS alone for managing this waste packaging was in excess of £33million. The burden of plastic waste associated with PPE has increased markedly since the onset of the COVID pandemic, with the vast bulk being disposed of by incineration due to concerns related to cross-infection. The rapid uptake of PPE – and issues related to the supply chain – have at the same time stimulated debate regarding opportunities to re-use these valuable barriers to virus transmission.

The inherent versatility of polymers that can be combined to create unique fit-for-purpose medical devices with complex shapes is also its Achilles heel when we consider how to manage the inevitable clinical waste stream. The established

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strategies for the management of plastic waste of *reuse*, *reduce* and *recycle*, are not readily applicable to the healthcare setting. Many of the polymers used are highly cross-linked and processed so that they may not be easily broken down into the constituent raw materials or derivatives. Polymer devices used in a clinical environment are at high risk of contamination, and the nature of the polymers and/or the complex shape of the devices makes it costly and difficult to clean, disinfect and sterilize. Devices assembled from multiple polymers in multi-layer constructs and combined (glued/welded) in complex shapes are very difficult/impossible to disassemble. Thus, *reusing* and *recycling* are not currently considered viable options for the management of this waste stream in healthcare. Recycling of pre-clinical plastic waste (products and packaging) that arise from manufacturing and distribution prior to being contaminated in a clinical setting is the more feasible option. The current linearity of the supply chain suggests that the most effective strategy to minimise the impact of healthcare plastic waste on the environment is by adopting a reductionist approach combined with innovative recycling approaches at both pre- and post-clinical contamination. The logical approach to reducing plastic waste in healthcare is by reducing the demand for this, which can be achieved through a promotion of better health focused on disease prevention coupled with the provision of high-quality interventions that do not require revising.

The main drivers for the different stakeholders in the supply chain are centred around their individual business models, with little attention given to environmental concerns that generally do not go beyond the need to operate within regulatory frameworks and meet corporate responsibility targets (*Figure 3*). The result of this approach is that the final fate of SUPs is not considered a challenge for each of the individual organisations in the supply chain, as the cost of disposal is borne by the final user. While superficially the clinical and regulatory determinants of waste generation and disposal appear to be defined, closer scrutiny suggests this may not be the case. To date, the most cost-effective management strategy in operation for this SUP waste stream is by disposal in landfill or incineration, with some additional examples of energy recovery in best case scenarios (3).

There is undoubtedly a huge opportunity to reduce the generation of clinical plastic waste, and to manage materials in a more environmentally friendly manner, but the challenges are significant. These include a risk averse culture throughout the sector, the need for compliance with complex regulations, challenges related to the identification and safe management of contaminated waste or complex-compound plastic devices/materials, and changing well-established culture and practices in medical and dental workplaces.

Figure 1. *Montage illustrating the variety, volume, and complexity of plastic waste generation in different clinical settings.*

These challenges for the management of the plastic waste all relate to the way that the supply chain operates; as the product moves along the chain, so does its plastic waste burden. This poses the question, could the management of SUP in healthcare form part of a circular economy? Through a series of proof-of-concept studies and interventions, we have attempted to establish a baseline of key knowledge that seeks to understand better the challenges associated with the management of SUPs in healthcare, and the opportunities that altered practices and emerging technologies present.

Results

Waste characterisation and quantification

Visits to a range of clinical healthcare settings were undertaken, including observation of orthopaedic, vascular, and dental surgeries. Observations and informal discussions were undertaken on initial visits, and it was determined that the majority of staff were aware of local waste plastic generation in their different settings. Something of the diversity of waste generated, and the challenging nature of a healthcare setting, is captured in Figure 1. Moreover, we noted that some local research had also been initiated, with parallel consideration of schemes to reduce the volume of waste. For example, one hospital theatre team had started to send non-contaminated waste to a children's art group (Children's Scrapstore, Registered Charity 1008788) for use in creative activities.

The Sheffield team also measured the volume and type of waste produced in adult dental care procedures, we identified the full range of generic plastic items used in these settings and quantified them for the different settings. The data from dentistry was gathered between October 2019 and March 2020 from three representative NHS dental practices and primary care provision in a UK teaching dental hospital clinic providing the full range of dental restorative procedures. The plastic usage from 130 dental procedures was recorded (*Table 1 and Figure 2*).

Type of dental restorative intervention (*Generic set up + specialty set up*)	SUP items per procedure
Restorations (fillings)	21 %
Endodontics (Root canal treatment)	20 %
Oral Surgery (Tooth extractions and minor surgery)	19 %
Crowns, Bridges & Dentures	16 %
Periodontics (Gum treatment)	13 %
Examinations	11 %

Table 1*. SUP items according to procedures in adult dental care.*

We identified that an average of twenty-one (n=21) SUP items are utilized in every routine adult primary care dental procedure in the UK. Our results highlight that the use of SUP items per adult care procedure is greatest in routine dental fillings, followed by root canal treatment, oral surgery for dental extractions/minor surgical procedures, provision of crowns, bridges and dentures and finally periodontics (gum treatment).

The most commonly used products are PPE for the dentist and nurse. On average, more than one pair of gloves, masks, wipes, autoclave/sterilization sleeves and tray liners were used with each patient, independent from the type of procedure delivered. This was compounded by the large number of items necessary for setting-up before and for decontaminating after procedures. In the UK, based on the number of registered dental care professionals (n>35,000) and considering an average of five procedures/day, it is possible to use this data to extrapolate the national usage of the approximate number of SUPs used in a 40-week working year. A mean of 21 SUP items/dental procedure translates to a conservative estimate in excess of 63 million dental SUP items/year that end up as waste.

The SUP items identified in this study were separated into into single plastics and multimaterials with multiple plastics forming compound structures (Figure 2). The latter are identified as posing a greater challenge for recycling. The breakdown is approximately 50:50 distribution. It is of note that many of the SUP items (e.g. gloves, wipes, masks and sterilization sleeves) are used beyond dentistry in other branches of medicine as well, their use does not relate directly to the specific procedure delivered.

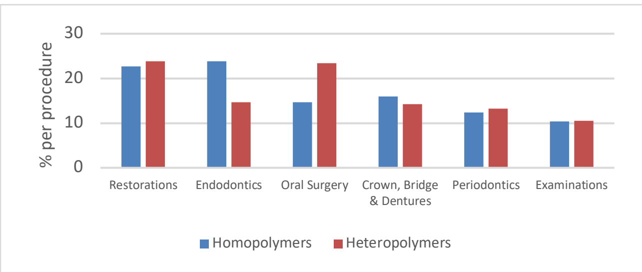

Figure 2. *SUP items according to composition. Single plastic (homopolymers) or complex compound items (heteropolymers)*

The organizational management of plastic use and disposal

We established that there is considerable variation in the application of regulations according to the size of healthcare organisations, and between different medical specialisms. While there are several policies and actors are involved in the management of plastic use and disposal, no regulation focuses solely on plastic use. These regulations are often disjointed and may produce contradictory outcomes, which allows very little opportunity to apply circular thinking. It was also noted that producers of medical devices and packaging were required to use virgin materials, which goes against one of the UK Plastic Pact's four key objectives, namely that by 2025 recycled plastic should comprise 30% of all packaging. On the other hand, procurement in healthcare organisations is driven by short term price reduction and efficiency on economies of scale. The environmental impact of products or even cost associated with waste management cost are not considered. In clinical practice plastic is seen either coincidental as in the case of medical device packaging, or the means of managing risks in the form of PPE. Finally, waste management is organized as an industry, hospitals need to contract companies who generate revenues by the amount of waste handled and processed. It is not their interest to reduce waste, and they might use risk related regulation to shield their own markets.

In summary, plastic products are extensively regulated in line with their pervasive application in healthcare services. Yet, these regulations focus on specific functions and risks associated with plastic products e.g. safety, protection, or contamination, and these factors were not aligned with each other. Moreover, waste management regulations were – perhaps understandably - focused on risks and costs, but did not consider environmental burden. This work highlighted the need for a more holistic approach to the governance of plastic products and waste, that at the same time was tailored to the specific hospital, practice, or healthcare organisation.

Public opinion and desire for more sustainable dentistry

To achieve significant and long-term improvements in the sustainability of dental services, engagement with policymakers, healthcare professionals, and the public is critical. However, previous research has largely focused on healthcare professionals (4) and no research to date has considered the role of the public in meeting these challenges. Research has, however, indicated that pressure from the public can influence healthcare policy (5) and drive change (6). Thus, evaluating the public's attitudes towards sustainability in dentistry may help to understand where changes to practice would be accepted and supported by the public; as well as inform future interventions designed to promote positive attitudes with respect to sustainable dentistry. To begin this endeavour, we have developed a questionnaire designed to assess the public's (i) attitudes towards sustainable dentistry, and (ii) willingness to make sacrifices in order to reduce the impact of their dental work on the environment.

Approximately 500 participants will be recruited online and in private dental clinics and asked to complete a questionnaire that will assess their attitudes towards more sustainable dentistry, their willingness to make sacrifices in order to reduce the impact of their dentistry on the environment, along with measures of general environmental concern and the extent to which participants engage in ecological behaviours. The findings from this study will explore whether more positive attitudes are associated with greater willingness to sacrifice for the environment, and how positive attitudes towards sustainability in dentistry relate to more general pro-environmental attitudes and ecological behaviours. The present research will provide valuable insights into people's attitudes towards sustainable dentistry and will enable policymakers and healthcare professionals to determine whether and where changes to dental practices are likely to be accepted by the public.

A role for innovative recycling?

There are two routes for recycling of plastic waste, mechanical and chemical (7). Mechanical recycling typically results in a lower grade product with limited applications. Chemical recycling considers the waste as a source of valuable chemical products useful as feedstock for various downstream industrial processes, requiring energy to break chemical bonds. Condensation polymers, such as polyamides and polyesters, can be depolymerised through reactions such as hydrolysis, alcoholysis and glycolysis with high conversion to their original monomers. Addition polymers, on the other hand, such as polyolefins (typically 65+% of municipal waste), cannot easily be depolymerised to monomers making them inefficient and expensive to recycle. Some polymers present significant chemical challenges, such as, PVC, which on thermal processing releases HCl and organic Cl-containing by-products.

One way forward is to redesign simpler products aiding future recyclability and circularity. The simple manufacturer changes to the plastic milk bottle resulted in both container and cap being made from a single type of polymer (HDPE). In addition, the recognition that a 75% reduction in the dyes used in the caps will enhance recycling by removing difficult contaminants. Identifying similar opportunities in healthcare waste, coupled with development of new chemical recycling processes are underway, for example, with a hydrocracking catalytic process tolerant of a mixed polyolefins (PE, PP and PS) with small amounts of PET and PVC, reducing rigorous collection and sorting regimes.

In healthcare, the collection of PVC masks from hospitals (RecoMedTM) gives an exemplar for sorting easily recognizable products on site. However, plastic products in healthcare have specific characteristics for a given application and often combine both condensation and addition polymers to obtain needed barrier properties and flexibility. They may be formulated as laminates or co-extruded materials (e.g. tablet blister packs and IV bags). This complexity of formulation is required for sensitive contents, and obtaining the required regulatory approval for change is a long process. Therefore, innovative recycling strategies to avoid complex, bespoke, expensive, multi-stage chemical separation and thermal treatments are required.

Discussion

From the outset, the experimental approach sought by this research group took note of the complex multi-faceted nature of the challenge that the management of SUP waste in healthcare presents. To meet this challenge, we identified and established a large and highly multi-disciplinary investigation team to deliver key project outputs. The data obtained from the various investigations conducted, has confirmed the importance of this strategy. Scientists from across the health sciences, bio-engineering, chemistry, geography and psychology have come together in this project to evaluate and assess, using highly specific experimental techniques, the diverse and interwoven aspects of this challenge, across the supply chain with the collaboration of multiple and diverse stakeholders. In addition to the tangible experimental output obtained from each of these groups, a major success has been the consolidation of a unique and powerful collaborative network of scientists across our academics in the universities of Sheffield and Manchester, industry, health-care providers in diverse sectors, NHS regulators, policy makers and waste management.

This research has established baseline data on the volume and types of SUPs that are used (and that create waste) in healthcare settings. We have provided new insights into the organizational models in which plastic products are used and disposed of, and undertaken a study of the clinical environments to identify opportunities to reduce waste generation by changing working practices. The project has also engaged with industrial partners to consider wider drivers of SUPs use and recycling. Finally, we have investigated public opinion, as the public are a major stakeholder with its dual role being a recipient of care and holding societal responsibility for the management of the waste. We have used dentistry to establish a common approach in these studies, being a self-contained or "boundaried" discipline with a large volume of procedures (circa 150,0000/day in the UK) and the need to adhere to strict regulatory frameworks. From this model, we have learnt lessons that could be translated to other day-case surgery healthcare environments. We have explored the opportunities and technologies for recycling these SUPs, and investigated which types of plastic waste are best suited to cost-effective recycling via innovative processing methods.

This research has provided new knowledge regarding the waste plastic generated in a range of clinical settings, along with public and organizational attitudes toward such practices and the need for more sustainable dentistry. Our findings have shown that a number of approaches are needed to reduce the volume of waste disposed of by incineration or landfill, accompanied by an increase in re-use and recycling. We also determined that – in both medical and dental settings - the bulk of plastic waste generated by the majority of clinical procedures was far greater than the amount of material required for the procedure. The focus of future waste reduction and recycling measures should therefore be on these forms of waste including gloves, packaging, surgical drapes, bibs, and single use instruments (and the main polymers associated with the manufacture of these items). Surveys of patients may also reveal willingness to make other sacrifices to promote more sustainable dentistry, such as using less aesthetically pleasing materials.

Reducing waste plastics in clinical settings will not be straightforward. There are undoubtedly some waste streams and polymers, in particular non-contaminated packaging, which may be well suited to material separation and chemical (feedstock) recycling using innovative methods. The multi-disciplinary work conducted by the authors in this and associated projects, has identified a distinct and common theme, namely, understanding working practices and changing local behaviours is key to reducing waste. There are a number of stakeholder drivers that pre-determine the management of CO_2 and plastic waste generated in healthcare settings (*Figure 3*). However, there is little consideration given to the 'environmental drivers', beyond meeting regulatory frameworks and corporate responsibility goals. There is a potential disconnect between procurement and waste management in healthcare settings that does not recognise the costs of disposal in purchasing decisions.

The authors have established that only a truly multi-disciplinary, holistic approach is able to address the full range of challenges in different clinical settings. This approach would need to accommodate both stakeholder and environmental drivers, and consider all stages of the supply chain from design and materials selection through to end-of-life waste management. Figure 3 summarises the various drivers and illustrates that the final "waste management" decisions are essentially predicated by all of the preceding steps.

Importantly, Figure 3 demonstrates that decisions made at each stage throughout the supply chain have the potential to change both volume and nature of waste generated, and also to increase the value of the waste (for example, greater re-use or as a feedstock for recycling). The greatest challenge – but one that has the potential to make the greatest impact – is to connect these disparate elements to achieve meaningful change.

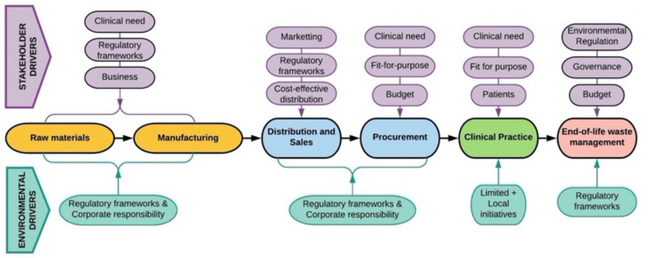

Figure 3. *Summary of the stakeholder and environmental drivers that influence the nature and final destination of waste plastic generated in healthcare settings.*

Conclusions

This paper has shown that the generation of plastic waste in medicine and dentistry is the result of a complex sequence of events and decisions made throughout the supply chain including purchase, use and disposal. The factors that determine decisions at each stage are complex, and include regulatory, quality assurance, safety, marketing and usage considerations that take into account clinical utility, price, and cross-infection control. Despite this multi-disciplinary complexity, there are undoubtedly opportunities to reduce the volume of waste that is incinerated or sent to landfill. For example, changing behaviours in clinical environments, increased focus on public health disease prevention and provision of high-quality interventions – coupled to improved waste management - has the potential to make a demonstrable reduction in the volume of waste generated, while new recycling technologies could additionally produce valuable products from selected waste streams at different points of the supply chain. While innovation in these different individual elements would be impactful, a far greater improvement could be achieved with closer integration between the different elements of the total product life cycle, effectively connecting material selection and manufacture through purchase and clinical use to disposal. This research has shown that a step change in waste plastic generation by medicine and dentistry is achievable, and further work is now needed to deliver these benefits. This collaborative research group, established as a result of this project, is actively pursuing opportunities to address these complex multi-disciplinary challenges.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

The research team wish to express their sincere gratitude to the following dental students from the School of Clinical Dentistry, University of Sheffield for their assistance in the gathering of primary data on the usage of SUPs in dental practice: Elinor C Durband, Leah S Hollingsworth and Olivia Kiernan. We also wish to acknowledge Dr Bilal El-Dhuwaib for facilitating access to dental practices.

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Session 4: Business & Social Models

Engaging Young People in the Circular Plastics Economy using Citizen Inquiry Methodologies and Creative Participatory Research Methods

Kevin Burden[a], Charlotte Dean[b], Fiona James[c] and Rudi Wurzel[d]

This paper describes a multi-disciplinary research project which explored the use of various creative participatory research methodologies including Citizen Inquiry to identify what young people really understand about and how they relate to the circular plastics economy. Within the scope of creative participatory research that the project espouses, the paper outlines a novel exploration of how Citizen Inquiry methodology can be used to engage and amplify the voice and actions of young people and work to foster genuine environmental agency amongst the young people who took part. The ensuing project also had an explicit international dimension that provided a comparison between youth-centred circular plastics economy related initiatives in two European cities (Hull, UK and Bremerhaven,Germany)

Introduction

Plastic waste has reached the 'alarmed discovery and euphoric enthusiasm' stage of 1. Down's (1972) 'issue-attention cycle' that predicts such positivity will quickly evaporate as the public realise the sacrifices required to resolve environmental issues of this nature. One proven strategy for avoiding this public lethargy is to engage people at a local level on projects where they can make a real difference and help keep issues high on the public policy agenda. One obvious example is environmental issues, and Citizen Inquiry, the focus of this project, is a novel methodology by which to engage the public in matters of genuine and personal interest to them.

'Citizen Inquiry' describes how members of the public can learn by initiating or joining their own inquiry-led scientific investigations such as identifying sites of 'fly tipping' or undertaking water purity sampling in a local reservoir (2. Sharples et al. 2013). The transdisciplinary project described in this paper brought together researchers from three different areas in the University of Hull (Education, Politics and Chemistry), along with external stakeholders such as community-based youth projects, schools and specialist education providers. The project was supported through internal pump-priming funds distributed as part of an Evolving a Circular Plastics Economy (ECPE) grant awarded through the Engineering and Physical Sciences Research Council (ESPRC). This paper focuses primarily on the way in which young people, in a variety of formal and informal education settings, engaged with Citizen Inquiry research activities and how this engagement impacted on their motivation, attitude and participation towards the circular plastics economy.

The paper includes findings from a comparator case study with young people in Bremerhaven, Germany, a city of comparable size and economical and environmental challenges to Hull, in order to initiate a wider understanding of the issues involved in engaging young people across different settings and cultural contexts. Hull and Bremerhaven have been chosen as case study cities for this project because they are both under-researched, medium-sized coastal cities with similar structural disadvantages including low educational attainment and high youth unemployment. Much of the existing research on local environmental initiatives has focused either on large cities such as London (UK) and Berlin (German) or on affluent medium-sized cities such as Bristol (UK) and Freiburg (Germany) the latter of which have played leading roles in European and/or global environmental city networks. Structurally disadvantaged medium-sized cities, which have remained under-researched, often lack the resources to get involved in such networks. However, emerging recent research on climate change innovations (3. Wurzel et al. 2019) has shown that structurally disadvantaged cities such as Hull and Bremerhaven have pioneered environmental innovations which have often been driven by local citizens including young people. Bremerhaven, in particular, exemplifies this assertion through its establishment of a Youth Climate Council (Jugendklimarat) and Hull demonstrates a strong commitment to issues affecting the environment through its Youth Parliament.

The paper also discusses and presents examples of an especially notable aspect of this project whereby several of the case study groups followed an impetus to influence and impact upon the environmental efficacy of children much younger than themselves through the design and co-creation of educational digital media platforms. An animated film, a digital game and two downloadable 'apps' were created during the course of the project which, their

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creators intended, would have the capacity to influence and educate those younger than themselves (typically primary school children) in the circular plastics economy.

Background to project

The Evolving a Circular Plastics Economy (ECPE) programme under which this project was funded, was an Engineering and Physical Sciences Research Council (ESPRC) funded programme awarded to a multidisciplinary team at the University of Hull led by academics in Chemistry and Geography. Using this funding, the university established the *Plastics Collaboratory*, a diverse group of researchers from various disciplines such as chemistry, geography, logistics, education and politics. The Collaboratory aims to understand the pathways and interactions of plastics in the environment, identify the gaps and leaks in a circular plastics economy, and explore and develop new pathways to an enhanced circularity in plastics use. The current project, referred to as 'The Plastic Citizen project' was just one of the several projects, within the Plastics Collaboratory, with the overall aim of tackling some of the key issues and challenges around the problems caused to the environment by excessive use and disposal of single-use plastic. The Plastic Citizen project aims to do this through examining the attitudes and approaches of young people to the issues relating to the circular plastics economy and by empowering them to undertake and share their own research using Citizen Inquiry methodologies.

Research Design

The overall objectives of the project were to:

- identify what young people know and understand about the circular economy
- work with EPCE scientists to develop a student friendly typology of plastic types for use in a Citizen Inquiry investigation
- test the feasibility of Citizen Inquiry methodologies in primary school age settings
- explore how young people centred initiatives (e.g. youth councils) can influence decision-making and increase their sense of environmental agency
- develop an international youth perspective on issues like the plastics circular economy to prepare future European funding applications around Citizen Inquiry
- create teaching resources to support the wider understanding of the plastic circular economy with different groups and students

These objectives were underpinned by the following research questions:

- What forms of public engagement about plastics related initiatives are young people currently undertaking in Hull and similar/contrasting settings (e.g. Bremerhaven)?
- How do Citizen Inquiry methodologies and other young citizen centred activities engage young people in the circular economy and the reduction of plastic waste?
- What can cities like Hull and Bremerhaven learn from each other about plastics related initiatives for and/or by young people?

With the project aim of engaging young people in the circular plastics economy, the University of Hull School of Education employed a post-doctoral research assistant (PDRA) with specific research experience in working with children and young people, particularly in utilising creative participatory research methods in researching the lived experiences of young people with a focus on the intrinsic commitment and understanding of the concept of voice (4. Cahill, 2007). Henceforth, the research was designed in order to create opportunities to acknowledge that voice, in terms of fostering each young participant's ability to express their thoughts and feelings relating to the issue of single-use plastics and also, importantly, to be encouraged to justify and back up any anticipated calls to action. To achieve this, it was important from the outset to acknowledge that facilitating the production of that voice is an interpretive process and involves an interaction between the researcher and the researched (5. Silverman, 2001; 6. Clough and Nutbrown, 2003). To this end, the PDRA employed was experienced both in designing research methods based around extracting and releasing the voices of the young participants, and was also a qualified youth worker who had worked with many youth based projects and schools in the region, a factor which served as an advantage in that the project already had access to a wide network of young people engaged with formal and informal education providers in the local area. The PDRA was supported by another researcher whose role was to observe the participatory research processes as facilitated by the PDRA and to initiate the development of a case study approach to focus on the specific activities emerging from each of the six settings which the project engaged with.

In terms of the project's approach to establishing itself as an attractive opportunity for young people to participate in, it was decided in the research design stage to address the language the team would use when discussing the issues relating to single-use plastics with young people. When we refer to the circular plastics economy, we are often using terminology born from scientific and academic roots rather than that which young people have identified and relate to. The research team aimed from the onset therefore, to explore the language that young people were using themselves around the plastics agenda through searching for the most used terms on online forums and social media. It was found that young people appeared to use the phrase 'single-use plastic' when relating to the reusing and recycling of plastics and no evidence was found to show that the 'circular plastics economy' was referred to at all by young people. The researchers involved in the project therefore refrained from using this term 'circular plastics economy' particularly in their initial introductory discussions with young people, and instead 'single-use plastics' was used as the topic with which to frame the research. In the process of observing social media sites and initiatives which involved young people, all had visible and eye-catching logos, hence the decision was made to 'brand' the project with the title 'Plastic Citizen' along with a simple logo in order that it could be easily recognisable and relatable to by young people (see Figure 1 below)

Figure 1: Plastic Citizen logo

A website (www.plasticsinquiry.com) was created in order to document the research carried out by the various youth groups along with a Twitter and Facebook account.

It is important to note that participatory research is "not a theory but an approach to praxis that uses any and all tools that co-researchers find helpful" (7. Greenwood and Levin, 1998, p.181). Participatory methods with children and young people, whereby the participants help design the research processes fosters the construction of methodologies that are more sensitive to how children view the problem, in this case, the problem of single-use plastics. Genuine interest to participate without manipulation was a critical factor that the researchers were mindful of throughout the project. The project design aimed to be empowering and potentially transformative, with a carefully considered exit strategy in the form of a competition for the 'best' (judged on a set of criteria pre-set in the research design phase) project that contributed to the circular plastics economy. As the main target groups for participation were predominantly under 16 years, the research team were careful to remain cognisant of the inherent power imbalances already existing between adults and young people. One of the objectives was to become aware of the meanings given by young people to the topic of single-use plastics, so it was important to be reflexive regarding how adult conceptions of the issue shaped those of children. The way young people's self-concepts may be changed and their conception of and interaction with their communities needed to be considered carefully throughout.

Informed consent was sought from the young people involved along with their parents/legal guardians and the Group Leader (head teacher or youth worker/leader) three weeks prior to commencement of fieldwork. A blanket consent form for young people's active participation in the project's design was issued, along with a clear and concise information sheet reflecting the activities occurring in the preliminary stages (participatory research activities such as idea-generation, photo-elicitation). Later on, as activities specific to each group/individual became confirmed, further consent was sought as required for the young person's participation in each activity. Any aspects of the research which potentially made an individual (as opposed to a group) easily identifiable (e.g. a drawing or video) would be anonymised in any subsequent reporting and writing-up of the research.

A significant ethical issue concerned gaining young people's 'assent'. Following parental/legal guardian informed consent, it was built into the research design that young people will denote assent in age-appropriate ways (e.g. through symbols, or cards with the options 'yes' or 'no'). Care would be taken to ensure young people would not be made to feel conspicuous due to their choices. In the interests of inclusion, it was intended that any young people whose parents had not provided consent would still be allowed to be involved, but no data would be used relating to that young person individually. As the project rolled out, it transpired that none of the above issues were pertinent as all young people gave their assent to be involved in the project through a simple yes/no response and there were no objections raised by parents in terms of restricting their child's involvement.

The project was split into three phases, it started by exploring the 'voice' of different youth groups to identify what they understand about issues related to single-use plastics and how they believe they can influence and impact upon it. This information was then used, as outlined above, to develop a participatory research design which included young people as co-researchers in designing their own individual projects aimed at engaging them in the circular plastics economy based on the following guidelines:

The projects designed by the young people were to:

- Encourage others to use at least one of the 4 Rs: Re-purpose; Reduce, Re-use and Recycle single-use plastic.
- Involve carrying out research – may be with other young people, may be local community, school etc.
- Involve digital technology in their design/execution.

The intention was that each of the six groups of young people that the project engaged would work either individually, in small groups or as a whole group together to design a project which would influence the circular plastics economy through tackling the problem of single use plastic utilising the 4Rs as outlined above. It was originally intended that the designs would be entered into a 'Dragon's Den' type event at the university in June 2020 whereby the young people would present their ideas and potentially win a prize for their youth project/school. Unfortunately, this event was cancelled due to the onset of the Covid-19 restrictions which were put in place in March 2020.

The Settings:

The project was undertaken across six different settings with various groups of young people as described below:

1. Year 5 primary school group (consisting of 38 mixed gender young people in Year 4 - aged 8-9, based in one primary school setting, this group engaged in 8 x weekly 2 hour sessions with the Plastic Citizen project)

2. International Pupil Council (consisting of 30 mixed gender young people in Year 5 - aged 9-10, these young people were from 15 different primary schools but came together as one group to participate in the project across 5 sessions)

3. Girl Guide group (consisting of 8 young females, aged between 11 and 15 who participated in 6 sessions with the Plastic Citizen project).

4. Environmental Youth Group (consisting of 9 mixed gender young people aged 11 – 16 who already met weekly to initiate environmental campaigns in their community and on a national level), this group participated in 8 x Plastic Citizen project sessions)

5. Alternative Education Provision (AEP) for young people with Social, Emotional and Behavioural Difficulties (SEBD) (consisting of 6 young people aged 11-14 who engaged in 6 sessions with the project researchers)

6. Youth Climate Council (An environmental activist group in Bremerhaven, Germany consisting of 14 young people aged 16 -18) and 3 x school groups (1 x primary and 2 x secondary) in Bremerhaven, Germany. (The research team included for this aspect of the project, a German speaking researcher who aided in translating the research tasks and activities.)

For each of the settings a similar format was adopted in that the researcher initially introduced the project through carrying out a series of icebreaker activities such as encouraging the whole group to stand in a circle and throwing a ball to each participant and asking each to think of an item of single use plastic when they receive the ball before passing on to another in the circle. This activity then developed into an activity called 'concentric circles' whereby the group splits in half, one half being 'speakers' and the other half 'listeners'. The speakers then move around the outside of the inner circle of 'listeners' and tell each of them a problem that can be caused by single-use plastics and then an idea that they have for solving that problem. The listener can then ask questions about the idea in order to refine it. The resulting ideas are then presented back to the whole group by the 'listeners'.

These are common activities synonymous to the participatory research methodology and can be adapted to explore any topic or questions that are pertinent to the research being undertaken. The activities also served to engage and relax the group and worked particularly well with young people as they were inclusive and could be adapted for any age range and ability. The next activity involved the researcher presenting an outline of what the project aimed to explore and then the context within which the project fit, this was done through talking through a Powerpoint presentation which included a short film about single use plastics. A group discussion was facilitated around identifying what the main issues relating to the use of single-use plastics was and then the Plastic Citizen competition project along with the associated guidelines was presented and the young people encouraged to work either together or individually to devise projects which would meet all of the guidelines as outlined above.

The international aspect of the project was provided by the various groups engaged in the project in Bremerhaven, Germany. The school groups consisted of 60 primary school pupils who participated in a 3 hour workshop with the Plastic Citizen project and then 2 classes of 24 secondary school students, each of whom participated in a 1.5 hour workshop with the project researchers. The Youth Climate Council participated in an informal discussion/focus group to discuss specifically how young people in Germany related and responded to the issue of single-use plastics. The subject related to their own formation and how they linked in with local governance and decision-making processes related to local and national environmental concerns. The results will be published in a forthcoming paper related to these issues and findings.

The Plastic Citizen project was notable in that it adopted the novel approach of facilitating a Citizen Inquiry 'mission' with one of the groups of young people, the International Pupil Council (IPC). This involved supporting them to co-design their own Citizen Inquiry research project based on addressing issues relating to the circular plastics economy and related environmental concerns. Traditionally, Citizen Science initiatives have typically engaged a demographic of white, middle aged, middle class men (8. Herodotou et al. 2018) who already present a considerable knowledge and confidence in their approach to engaging with scientific concepts and issues. Citizen Inquiry is a methodological approach born of the intersection between Citizen Science and Inquiry-based learning and aims to broaden this demographic typicality by enabling Citizen Science to transcend boundaries, not only social (age, class, ethnicity) but also academic, through facilitating a cross-discipline approach. Websites such as Zooniverse.com perfectly illustrate this approach through presenting Citizen Science style investigations in fields such as literature, botany and even the social sciences. It is this foray into adapting Citizen Science type research for social science investigations - in this case, the engagement of young people in the circular plastic economy that this aspect of the research linked.

Research Outputs and Outcomes

In terms of research outcomes and outputs, the project has elicited six case studies based on the participation of each of the projects as outlined above. These case studies have led to the emergence of a number of key findings which are outlined individually in the discussion section below. At least two academic articles are currently in the process of being submitted to relevant international and interdisciplinary journals, one is based on young people's perceptions and factors relating to their engagement with the circular plastics economy and the other on the impact of utilising Citizen Inquiry methodology based on the pilot with the International Pupil Council as outlined in the Research Design section above.

Other notable outputs have been the creation of two user-designed digital 'apps' to engage and educate primary school children in activities relating to the 4R's. The young people involved in the various projects have also produced a number of learning resources, again, designed to be used with younger children. These include a set of jigsaws based around the 4Rs; a series of posters to be displayed in schools/youth settings to encourage young people to recycle their plastics; designs for recycling bins to be installed in a school dining hall for children to recycle any single use plastics in their packed lunch boxes; planters made out of recycled plastic to be installed in a school playground for growing edible produce; a story book, aimed at younger children containing fun facts about how children can contribute towards a circular economy and an animated film made with a local arts production company which will be available on YouTube and will also be linked to supporting activities and resources on the project website.

The young people who initiated the Citizen Inquiry project utilised the Open University's nquire platform to create an online inquiry into the recycling habits and attitudes of their local residents. They then presented the results of their survey along with a report based on their ensuing analysis of findings to the Lord Mayor of Hull. Another group instigated a piece of research with over 100 other young people which was presented at the local Youth Parliament. They also facilitated a plastics sorting activity at the same event whereby they presented a selection of single use plastics for other young people to sort and classify according to the type of plastic it was. Several of the projects included aspects of creating prototype apps to identify the seven main different types of plastic in order that the subsequent collection and processing of post-consumer waste can be greatly simplified. The young people anticipate that their apps will enable consumers to distinguish between the different types of plastics and recycle accordingly.

Other outputs included teaching resources developed by the research team in order to facilitate the ongoing engagement of the young people in the project upon the onset of the Covid-19 pandemic. These resources were made available to the young people via email to each project group leader/teacher and also housed on the project website. Other communication methods were facilitated in order to maintain the momentum of the project including meeting through online conference platforms such as Zoom. In order to best safeguard the young participants in these online endeavours, the team created a digital safeguarding protocol which outlined the protective measures to be put in place for any online activity such as the use of an online waiting room in order to approve all participants before accepting into the meeting and password protection for video conferences.

Discussion

Each of the six case studies showed that although the same or similar engagement and research methods were used for all of the projects, there was a notable disparity in the overall response to the project across the different settings. This appeared to be mainly influenced by whether the young people engaged through a mainstream schooling session or a more informal education setting such as that relating to a youth group. Those young people engaged through a school setting appeared to require more structure in terms of preparing resources (such as drawing templates, Powerpoint presentation and worksheets) whereas the informal settings, such as youth groups which were not linked to a school appeared to respond to less structure and also showed a much higher level of autonomy and self-direction in response to the project brief.

A positive aspect of the participatory research methodology was the ability for the specific activities designed by the research team to quickly engage young people fully in the research. An example of where this worked particularly well was through the use of the icebreaking activities, which effectively enabled the young people to explore their current knowledge of the circular plastics economy whilst providing an indication to the research team of the level of this current knowledge. The icebreakers worked equally well with both primary and secondary school age groups, illustrating their adaptability in terms of utilising research methods which are flexible and responsive to the age and ability for young people participating. They also worked well when delivered with the school groups in Germany, a factor which illustrates the inclusive nature of participatory research methodology.

Whilst the young people demonstrated and repeatedly voiced their deep concern about the impact humans are having on the planet, they also indicated that they never or rarely heard about issues relating to sustainability or climate change in the classroom – this was particularly pertinent to those in secondary education. However, despite a lack of formal education on the issue, the research did show that young climate change activists like Greta Thunberg are inspiring young people to take matters into their own hands (9. Burns, 2020). The young people in the study indicated that their information and education about issues relating to climate change and plastic pollution tended to be gleaned from online sources and television programmes such as the BBC production David Attenborough's Blue Planet.

The research showed that almost all of the young people who participated in the project felt they demonstrated increased awareness about issues relating to the circular plastics economy, though their concerns were focused mainly on the impact that they could have on the recycling aspect. Promoting sustainability at home emerged as an important focus, with the majority of young people saying that they would try harder to recycle and also would be encouraging their parents to recycle. The young people described events whereby they had used their increased knowledge about the different types of plastics and their recycling capabilities to influence their parents buying choices when out shopping with them. They also said that through their involvement in the project, they tried to use products that are ethically made and are not harmful to the environment or society, however, several young people identified that this was very difficult for them as they did not have financial control over the buying choices within their family, therefore, their ability to shop more responsibly depended on the level of influence that they could engender over their parents.

Conclusions

This project has shown that the use of participatory research methodology, particularly Citizen Inquiry has established a way forward for making a significant contribution to tackling the key problems in the circular plastics economy. One of these is the ability for consumers to be able to distinguish and separate different types of plastics, including recyclable, non-recyclable, biodegradable and compostable. The young people in the project responded to this need by creating a variety of digital learning resources and teaching/learning activities for other young people to engage with. The revealing of young people's impulse to adopt the role of educators of children younger than themselves has been another important aspect of this research in that young people have intentionally positioned themselves in a peer education role, studies about the effectiveness of which have remained largely unpublished (10. Backett-Milburn and Wilson, 2000). 11. Heron (1996) suggests that participatory research co-created with others, repositions the participants (in this case young people) as researchers rather than those being researched. This has been exemplified in this project through this aspect of young people carrying out research 'for' other young people rather than just 'by' young people. Only by shifting the practice of researching 'on young people' to 'with young people' can we hope to facilitate research which is empowering, emancipatory and effects real change in the lives of young people.

The majority of young people feel their generation is under pressure to solve environmental issues such as climate change and plastic pollution but do not think they are well-enough equipped to make a difference (12. Young, 2019). This project moves some way towards resolving this issue through placing young people at the forefront of identifying, researching and developing collaborative approaches to teaching and learning resource deficits through the co-creation of a needs-led, responsive Citizen Inquiry led solution.

Conflicts of interest

There are no conflicts to declare.

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"There is no problem with plastics": Understanding consumer and industrial perceptions of the plastics problem

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The proliferation of plastics waste and its polluting effects have been thrust into the public eye following high-profile media attention, which has given plastics a pre-eminent position in UK circular economy research and policy debate. Devising policy solutions, though, requires having sufficient understanding of an issue to frame a problem to which there are identifiable solutions. Although interpretations and preferences inevitably vary (both between and within different social and economic sectors), a level of collective understanding and agreement is needed to successfully design and implement policies. As part of the formal regulatory process of consultation, organisations and individuals independently submit comments for review by government staff. However, circular economy-inspired solutions require practical solutions which need to work for multiple stakeholders. This paper reports on a novel analysis of transcripts from two workshops with diverse regional stakeholders partnering the University of Hull "Evolving a Circular Plastics Economy" project. We posed a series of discussion topics in order to uncover the social actors (stakeholders seen as taking active or passive role in a given context) identified and the representation of the relationships between them. We note how certain actors and their relationships are variously foregrounded or ignored within the discussion, with the discourse therefore legitimising only certain actors, and framing their actions within a market/economic relationship. The fact that the project partners present comprised only a selection of plastics stakeholders demonstrates the need to be part of the debate in order to contribute to the definition of "problems", which is necessary to be accepted as part of the definition of the solution.

Introduction

Plastic is fantastic. It is flexible, light, versatile, resistant to corrosion and cheap. It is also durable; its persistence in the environment, as whole products or as microplastics, means that it increasingly impacts life in the ocean and on land (e.g., impeding soil fertility (Duis and Coors, 2016; Zheng et al., 2019). Of particular concern is single-use plastic, including the vast majority of plastics packaging; an estimated 72% of which is not recovered at all, being sent for energy from waste or to landfill (Ellen MacArthur, 2016). There has been significant research in response to the environmental impact of plastics, focusing on technical solutions (Crippa et al., 2019), such as the need to improve the quality of recovered plastic (Hahladakis and Iacovidou, 2019), or to develop new plastics, such as bio-based, which do not rely on petroleum-based limits for supply, or biodegradeable which might potentially avoid significant pollution issues (Spierling et al, 2018). The plastics issue is at heart, however, a social problem. That is the problem is not necessarily (or primarily) related to the material itself, rather than to how it is used and, importantly, what happens when it has served its purpose.

Since plastic is embedded in our everyday life and is used in a variety of sectors, its ubiquity means that solutions must be varied and involve the application of numerous academic disciplines and consultation with a wide range of stakeholders (which we define broadly as any organisation/individual with an interest, not necessarily economic, in the issue). The circular economy (CE) approach recognizes the systemic nature of resource and (potential) pollution issues. By moving away from waste, and even recycling activities, through better systems and improved design, environmental damage is minimized and resource efficiency maximized (Ghisellini et al 2016). CE has been adopted by policy-makers as offering a means to reduce the environmental impact of plastics (EC, 2014; Defra, 2018). Yet application of a CE approach, potentially attractive to policy makers because of its specific methodologies for implementation (Cecchin et al., 2020), by no means provides straightforward or uncontentious solutions.

CE approaches require the involvement and a reprioritization of a wider and more diverse number of stakeholders, together with an understanding of their issues. Previous research indicates that EU policy documents identify business and consumers as the major actors in the transition to a CE (Lazarevic and Valve, 2017), implying "governance by corporate business" (p 67), with the state in a supporting role. At the UK scale too, plastics have been primarily constructed as a business problem, reflected in the WRAP "Plastics Pact" (WRAP, 2019). Of note, business is not a homogenous group, any more than are consumers. To achieve the UK Government's goal of increasing plastics recovery by means of consistent labelling and recycling schemes throughout the country requires agreement between stakeholders including packaging manufacturers, food wholesalers and retailers, local authorities, waste management companies, plastic re-processors, not to mention the public. To increase the challenge, not all of those stakeholders are necessarily based in, or entirely operating within, the jurisdiction of UK policies.

In this paper, however, we are taking a step back from attempting to directly solve the problem of plastics. Instead we want to uncover some of the assumptions behind policy prescriptions, in order to shed light on the process and improve the likelihood of policies succeeding. We are applying a cultural political economy (CPE) approach (Jessop, 2010; Sum and Jessop, 2013), which asserts that the language within which policy is set is not neutral (Jessop, 2010). Instead by a process of inclusion and exclusion of stakeholder perspectives it normalizes certain possibilities within what becomes effectively a simplification of reality (called an 'imaginary' in CPE terminology). CPE can provide an account of how objects of governance come to be defined and operationalised. Even evidence-based policy making is not an objective process: the solutions selection will reflect the problems definition (Bacchi, 2009), which in turn reflects who is part of the process of definition of the problem.

In order to operationalise CPE in this paper we are employing critical discourse analysis to explore the rapidly developing collective conceptualisation of plastics as a "problem" to be addressed in the UK economy. Critical discourse analysis is an established academic approach which studies language in text to highlight agency and uncover structural inequalities between governing and governed (Farrelly, 2019). The language in which issues are articulated is important because of how it shapes expectations: language inspires action; legitimises and sets up the conditions necessary for co-operation. The use of a shared language makes policy and legislation formation and implementation more effective and quicker; allows participants to understand issues and barriers, thereby saving time and costs. Language itself thus contributes to the construction of a collective programme for action based on a very partial understanding of a problem. Language is an important aspect of the legitimising or construction of narratives contributing to the collective imaginary, i.e., definition of the problem to be governed. A key question arises, though, as to which stakeholders (or social groups) are recognized as legitimate participants in the process.

Innovatively, the text analysed in this paper comprises transcripts from a workshop organized for the plastics stakeholders collaborating with the University of Hull's "Evolving a Circular Plastics Economy" project. Consideration of the language used provides a significant additional insight as opposed to simply seeking opinions, or trying to derive information ("facts") from the discussion. Following Farrelly (2019), we are primarily concerned with 1) identifying how the plastics stakeholders comprising our project partners represent the "plastics problem" in terms of who are the relevant social actors and 2) are those actors represented as having active or passive roles in the problem?

The next section outlines the key aspects of the approach from CPE and CDA; we then provide a detailed account of our methods; then analyse the social actors emerging from the workshops, before providing a discussion of the findings and offering brief conclusions.

Building a critical approach

Cultural political economy (CPE) (Jessop, 2010) examines how we make sense and meaning from our interactions with the world and is a relatively novel way of analysing policy. According to Jessop (2010) economic governance inevitably involves a process of complexity reduction:

Because the world cannot be grasped in all its complexity in real time, actors (and observers) must focus selectively on some of its aspects in order to be active participants in that world and/or to describe and interpret it as disinterested observers. (2010, p. 338)

Thus, those who govern, in the absence of full knowledge and control, engage in practices of complexity reduction. Collectively, institutions of governance, and the people at work in them, are able to create what is, in effect, a subset of an economy and develop methods for measuring and controlling that subset. These complexity reducing practices entail prioritising certain elements of economic activity and, no less importantly, de-prioritising others. The products of complexity reducing practices are, in CPE terminology, "imaginaries": these imaginaries both reflect and constrain individuals' experience of the complexities of the world and thereby influence collective understandings of how to respond to/manage situations (Jessop, 2010). Imaginaries become the objects of governance; or in other words, imaginaries are collectively constructed simplifications of real economies. In this paper we examine the plastics "imaginary" constructed by the stakeholders involved in this project.

Although we can view imaginaries as a necessary part of the practices of governance, we can also view specific imaginaries as contingent - that is, neither inevitable or necessary. Instead, we can see specific imaginaries as subject to processes of variation, selection and retention. There are several modes of selection - ways in which imaginaries come to be selected. Particular agents occupy social positions of influence and the abilities and preferences of those agents comes into play in the selection of imaginaries. Drawing also on the terminology of critical discourse analysis, we can refer to those influential agents as social actors (Farrelly, 2019). Social actors, in this sense refers to the representation of human participants in texts. An analysis of these representations can reveal biased representation, witting or unwitting on the part of a speaker or writer, toward certain social groups or individuals. We contend that the analysis may reveal that patterns or habits of textual representation are not fully adequate to describing current circumstances or desired policy outcomes. As Farrelly argues "the representation of social actors in texts can reveal important underlying conceptualisations of the circumstances of policy interventions" (2019: 147). Non-human actors can also be ascribed the properties of a social actor by the practice of anthropomorphism (Epley et al., 2007), by which they are implicitly or explicitly credited with motivations and agency attributable to humans. Although a fairly common figure of speech, and not necessarily motivated by an intention of dissembling, the practice of anthropomorphising can contribute to the non-representation, or exclusion, of potentially significant actors within imaginaries. The explicit identification and analysis of the actors perceived as relevant in the developing collective imaginary remains a significant gap in the literature which we address in this study.

Methods

This paper draws on University of Hull's "Evolving a Circular Plastics Economy" project, which involves researchers from a range of disciplines and partners drawn from industry, local government, and NGOs in the region (Figure 1). The partners, who have formally agreed to participate in the research, are drawn from the wider population of stakeholders, who could be representatives of any organization with an interest (economic, environmental or social) in the production, use or recovery/disposal of plastics. Our partners were largely drawn from the Hull and East Riding area of Yorkshire. Hull is a coastal port of c260,000 (Hull data Observatory, 2019) located approximately 180 miles north of London. The fourth largest city of Yorkshire, following the decline of its fishing industry, Hull ranks as the fourth most deprived local authority in England on the index of multiple deprivation which considers income, employment, and health outcomes (2019). Current major industrial sectors include chemicals, healthcare and food processing. The East Riding of Yorkshire, which surrounds the Hull area, is the largest unitary council area in England and significantly more affluent than Hull (overall), and predominantly rural rather than industrial.

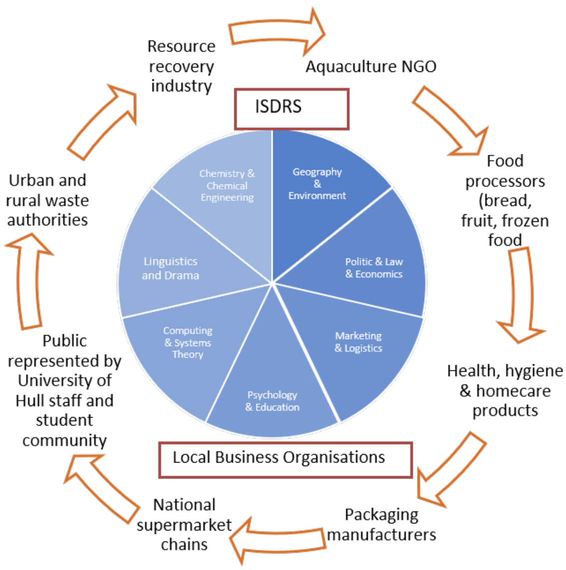

Figure 1: The Evolving a Circular Plastics project network comprising 15 disciplinary perspectives industry, government and non-governmental organisations with representation in the region. Not shown here is the advisory board with national and international non/governmental and academic representatives.

Data for this paper is drawn from two stakeholder meetings held 28 February and 6 March 2019 at the University of Hull. The same event was run twice to accommodate the availability of the project partners. These workshops served an important function of communicating the relevant research capacities to the partners. They enabled connections to be built between them and not only the stakeholder-facing (i.e., social science) researchers, but also the laboratory-facing (science and engineering) researchers. A number of subprojects emerged as a result of these connections, specifically focusing on partners' interests. More relevant to the present paper, however, is the other function of learning from the partners what their perspectives on plastic were. We thus aimed to establish a common understanding as we embarked on a shared journey.

The concept of the World Café (World Café, 2015) was used to structure proceedings. The World Café method aims to encourage diverse participation and co-creation of knowledge in an informal setting which is designed to break down barriers to contributions. Participants are encouraged to share tacit information in a non-hierarchical way, to encourage collaboration. Attendees were split small groups (Figure 2) comprising a mixture of both partners and academics to discuss a number of questions with academics and stakeholders evenly spread as much as possible. The workshops were divided in two sessions a) Problem exploration and definition and b) Defining the circular economy. This paper focus on the first of those sessions, which addressed the questions "Why do we (society) use plastics?" and "What problems do plastics cause and why?" These very broad, and superficially easy to answer, questions, were designed to generate discussion amongst participants in order to capture their perspectives at the outset of the project. We sought to uncover how the participants are understanding issues relating to plastic, and to derive from that who are seen as the groups with agency, or actors. Each session had a dedicated scribe to take notes: participants also completed post-it notes on questions. Full-group discussion allowed for the most important findings to be shared, permitted partners to ask questions and make further comments.

Figure 2: World Café workshop with regional stakeholders

Participants gave written consent for audio recording, photographs and the use of anonymized and/or generalized contributions in publication.

The data were transcribed, and texts analysed utilizing NVivo software in order to compare how different stakeholders construct the plastic imaginary. For the identification of actors and their roles we used the critical discourse analytic framework first developed by Van Leeuwen (1996, 2008) in which he gives an inventory of the ways social actors can be represented in (English) discourse (1996, p. 32). Following Farrelly (2019), our analysis of the representation of social actors has two distinct elements:

1. Identification of representations of social actors – who is being represented
2. Categorisation of those social actors – are they passive or active?

First, we identified the processes and actions that were represented in our data which would require the participation of human beings. Where these actions included a representation of human participants, we coded those as "social actors: included"; where the actions were not represented with a human participant we coded them as "social actor: excluded".

Second, we categorised the "social actors: included" as for further aspects of how they were represented. That is, whether they were represented as passive (influenced by the actions of others but lacking agency themselves) or active (having and apply the ability to influence outcomes to some extent).

Analysis

Our analysis shows that the partners collectively had four major categories of social actor in their understanding of plastic in the UK economy. Three of these were society, business, and the consumer. In addition, and less expectedly, plastic itself is often seen as having agential qualities, as though it were a social actor. We present detailed analysis and examples of each category in the following sections.

The Representation of "society" as a social actor

Society is represented as one of the major social actors throughout our data, society is common in how the contributors to our data conceptualised the contemporary plastics problem. In this paper we focus on explanatory examples.

In example 1, sentence 1 shows society as having shared, and historically common, problems:

Male 5 : Yes… it [plastic] solved so many of the problems that human society had lived with for thousands of years, you've got this wonder substance that does all things for all men and you can just find more and more uses for it and more and more ways in which it can make people's lives easier and…

Male 6: Convenience, yes.

Male 7: It's replacing other resources…

The most obvious social actor in sentence 1 is "human society"; but this is a social actor that is the passive recipient - or at least is seen as being unable to deal with - many problems. Less obvious as an actor, but important none the less, is the personification of plastic. Plastic, "it" is the entity that "solved" the problems that human society had lived with.

Furthermore, in sentence 3, plastic is represented as though it is the active agent in "replacing" other resources - it is not people, or social organisations, that are repressed as undertaking the actions of "replacing" other resources.

The Representation of "business" as a social actor

Business is represented as one of the major social actors throughout our data, business is ubiquitous in how the contributors to our data conceptualised the contemporary "plastics problem".

In example 1, sentence 1 shows business being contrasted with the personal motivations of the speaker:

1. So there's two aspects to it. (4.42) There's why do I use it and why does a business use it.

2. So flexibility of use, you know plastic covers many different aspects of packaging so it's just convenient for us to use.

3. It's incredibly cheap compared to other solutions so consumers are incredibly price sensitive and so we try and offer the cheapest solution that we can, especially compared to what else is in the market.

4. It allows us to maximise product life so protecting the integrity of the products as well as increasing shelf life.

Interestingly, the conceptualisation of the plastics problem shows a significant absence of social actors. In sentence 2, we see that business is represented as the only social actor, and this is interesting because there are several important social actions that are included but for which social actors are either implicit (backgrounded) or absent (suppressed). These actions are:

- flexibility of use

- to cover

- to package

The action "to cover" means something like "we use plastic for several different purposes" but in the actual representation of the business and its needs and preferences for how it uses packaging are backgrounded. Similarly, in sentence 3, the use of the word "solutions" implies a problem that business has without stating so in direct terms.

Note that plastic is represented as though it is a social actor with a metaphorical capacity for agency in sentence 4: it is plastic that is said to allow business to maximise product life. This analysis is not a criticism of the individual speaker, rather, we suggest that it is revealing of a discourse in which causal effects are attributed to plastic. This representation suggests that, in this conceptualisation, businesses are limited in their capacity to act.

The Representation of "the consumer" as a social actor

"The Consumer" is the third major representation of social actors in our data, and is a clear part of how the contributors conceptualised the contemporary "plastics problem".

In example 3, shows the consumer in relation to the business that we saw above in example 2:

*1. It's incredibly cheap compared to other solutions so **consumers** are incredibly price sensitive and so we try and offer the cheapest solution that we can, especially compared to what else is in the market.*

2. It allows us to maximise product life so protecting the integrity of the products as well as increasing shelf life.

3. Alternatives seem to fall down at those aspects.

4. There's the protection during transport as well so plastic is incredibly useful for that.

5. The ability to print and customise and create your own designs, effective printing direct onto products and creating your new and bespoke mould.

*6. And from a **consumer** perspective I think there's just very few alternatives available.*

*7. Also when **you're **in the shop and **you're** looking to buy products, there's very few kind of plastic free alternatives out there so you're almost kind of shoehorned into buying plastic and using it.*

Sentence 1 represents an aspect of the consumer identity, that is a quality of what it means to be a consumer, that quality is that they are "incredibly price sensitive". In representational terms this sensitivity is show here as a reaction to price, rather than being the result of a more active decision-making process.

Sentences 2-5 describe the qualities of plastics that allow business to accommodate the price sensitivity of consumers and, in sentence 5, to allow business to market products to consumers.

Sentences 7 and 8 describe consumers as being rather helpless in the face of the ubiquity of plastics. Interestingly, the "consumer" is represented without any hint that consumers may be a heterogenous group; as a consumer one has little choice: "you're almost kind of shoehorned into buying plastic and using it"'.

Plastic as an "anthropomorphised social actor"

As mentioned, there was a significant representation of plastic as an anthropomorphised social actor. We found, in the discussion of the question "what is the plastics problem" that of the 139 instances of the word "plastic", 118 of those referred to plastic in a material sense, but 21 referred to plastic as though it had some human, agentive or causal property. Table 1 shows each of the 21 instances in which plastic is represented in these anthropomorphise' terms. For example, "It's unnecessary, problematic plastics, that are proliferating in to society"; represents plastics in a way that makes it appear that plastic has the ability "to proliferate" without representing the human activity, social organisation and group decision-making that leads to the greater production, circulation and use of plastics in society.

Table 1: Examples of the anthropomorphising of plastics by workshop participants

Example number	**Content**
1	And, it is important that you don't end up demonising plastics because there are so many ways in which it does provide positive results for society and it does allow us to live longer and healthier and more fulfilling lives.
2	Male: You can't blame the plastic bag; it's the – what does that famous rapper(?) say?
3	Yes, it's not the plastic bag, it's the person who threw it away.
4	So, we're now at the point of single use, throwaway is now associated with plastic, whereas we wouldn't (inaudible 0:04:30) have people? there are – we're at the point where we're vilifying it because it's poorly managed.
5	It's unnecessary problematic plastics that are proliferating in to society.
6	It's a generalisation, but the older you get, so generation x, y and z, huh, the older ones of us, we're the harder ones to bring round, purely because we've been indoctrinated into plastic is good, it's the new way. It's the generation.
7	This is why not all plastic is bad. Plastic is good.
8	Plastic is good. It's more about educating people what to do with it.
9	That's where plastic is-Male 2: But because there are all those different categories of plastic, and there is some plastic, I think it's the thinner type of- Propylene, why it's not recyclable and there's-
10	And that's even worse than pure plastic.
11	I mean plastic has been demonised and not all plastic is bad. Some are worse than others.
12	Equally, not all plastic is bad, but some are worse than others. Male 2: Did you say PVC, sorry, did you say?
13	The plastic acts- A good frame to bond all that, everything, together. Male 1: Yes, I mean-
14	So that's why plastic has a lot of benefits, so people use them more and more. I think I remember figures, water

	produced worldwide each minute, 1 million, I think a couple of years ago.
15	And that's partly because the problems associated with plastic are outsourced to society, not held within the businesses that develop or they create products and outsource to everybody. So, they've socialised the costs.
16	The responsibility of plastic.
17	Plastic is just part of that one simple- of that, that's facilitated or enabled that to happen.
18	So, plastic does have benefits through the supply chain. So, when it's transported to us before it's used, it is very lightweight.
19	I think what plastic enables a society is to move from canned food to more frozen food.
20	There's nothing inherently wrong with plastics, it's what you do with them when you just use them, that's the problem. That, for me, is the ___[0:11:51].
21	Plastics have a role and use within society, but there are places where it's about how we can more effectively recycle them and remanufacture and reuse them in other products.

Some of these instances represent plastic as being evaluated in moral terms – as good or bad; some represent it as though others have evaluated it in terms of human morality – "I mean plastic has been demonised and not all plastic is bad". It is notable that more than half of these examples are supportive of the use of plastic, emphasising that the material is not an active agent in the environmental harms often credited to it. The raises questions as to what the participants may consider the causal factors to be, and consequently what might be effective and acceptable solutions. Interestingly, many potentially active agents are not defined as social actors in our data.

Absent social actors

Our analysis found important absences in social actors from the texts. No contributor referred to any of the following:

- government
- citizens
- voters
- electorate
- scientist
- academic
- manufacturer

These political, research and manufacturer categories were entirely absent from our data on this question, suggesting, perhaps, that the discourse is not one in which plastics are seen as a political, research issue. Indeed, representations of these social actors was absent from our entire set of transcripts for all questions. This is more surprising since we found a range of activities and processes in our data which might be considered to belong to the realms of political economy, research and innovation, or the manufacturing industries but still, the social actors involved in those processes were excluded. For example:

- political economy: *"It's globalisation"* - the processes of globalisation is represented without reference to the political or economic actors which enact it

- research and innovation: *"a lot of the innovation has happened in the developed world"* - those who carry out research and development for innovation in plastics are excluded here

- manufacturing: *"At the moment it's easy to manufacture the different types of plastics*." - although the manufacturing process is included, manufacturers are not.

What this indicates is that, in our data at least, there is an important selectivity in who is represented in discussion of plastics.

Discussion

In this section we consider the answers to our two research questions (who are the social actors and are they represented as active or passive actors) together.

Although the question posed to the workshop was framed in terms of why we as a society (i.e., collectively) use plastics (not, why do "you" use plastics), the ensuing discussion was strongly influenced by the identify of participants. The inclusion of business and consumers amongst the social actors is not surprising, given the composition of the group (including consumer facing businesses). This is consistent with the nascent plastics imaginary that already exists at the EU and UK scales of governance (e.g., Lazarevic and Valve (2017; WRAP; 2019). The prominence of the food industry (broadly defined) amongst the partners reflects composition of industry in the region, and steered discussion towards packaging examples although we had no-predisposition towards that product.

Despite the focus on issues relevant to participants, society also emerged as a significant social actor, but more as a repository of collective problems, than as a source of solutions. Interestingly, plastics themselves emerge as more heroic actor – with the ability to solve society's problems. This writes out of the story the scientists and industrialists who developed new forms of plastics, not to mention the advertisers who promoted them, and the consumers who rather swiftly and comprehensively adapted their behaviour in keeping with, and simultaneously constructing, the narrative that plastics are virtuous.

Regarding plastics as a social actor suggests it has agency outside that of human control, meaning that arguments for political control are immediately undermined. The lack of specificity around the many different types and uses of plastics suggests that it is easier to discuss plastics in this generic way but also that it exists in its own right, with other properties usually limited to human actors such as a moral sense. This framework underlines how much plastics are perceived as a part of everyday life, to such an extent that they are accepted and resistant to change, a comparison might be made to the weather or another force of nature. Our stakeholders were drawn from industries which might be expected to effect change in societal use of plastics, such as food packaging companies or supermarkets, but they clearly found it challenging to conceive of ways in which plastic might not exist.

A key relationship to emerge from the discussion is that between the social actors of business and consumer. In this discussion, again reflecting the fact that although everyone in the room was a consumer, we were all present in our professional capacities (which for a significant proportion was business). The consumer is portrayed in the text as the more passive actor e.g., choosing from what is available, primarily sensitive to price. This is seen as a constraint to business; it is portrayed as the consumers fault somehow that businesses cannot do more. However, the problem perhaps is not so much the fickleness of consumers as the need to compete with other businesses. A notable absence was the mention of government or policy-makers, who, after all, could remove the element of competition by regulating for more packaging that is easier to recover (or whatever approach to circularity might be adopted).

Notably, the discussion lacked a nuanced view of the social actor categories. In particular, there is a very one-dimensional view of people as consumers, i.e., not citizens, or victims of pollution – or for that matter as voters, or campaigners. Indeed, even consumers are highly variable in their tastes, budgets and behaviours. The emphasis was therefore on market relationships – consumers are customers, or potential customers. The implication is strong that the plastics imaginary is financially defined as least as much as it is environmentally (though perhaps this is a sign that the discussion was conscious of solutions more than driven to the nature of the problem). Thus imaginable (i.e., acceptable) solutions to the plastics problem are likely to be pre-defined by affordability to business.

Conclusions

In this paper we have argued that understanding who is considered to have agency is an important part of finding a consensus and policy solutions, particularly within a CE framework.

It is striking how social actors with market relationships (primarily business and the consumers) are foregrounded in the discussion, with government actors and policy tools such as regulation almost totally absent. Plastics are conceptualized as intrinsically part of the market economy, suggesting that solutions will need to fit this picture too. Government, citizens, environmental groups etc have a very limited role, it seems, in bringing about changes. Therefore, there is wider work to be done in cultural terms to extend understanding of the CE concept, and move away from a very market-based story.

Given the way in which plastics have become materials of choice in society, and are seen as problem solvers even whilst new problems are recognised, there is an implication that change can be dramatic if it is suiting the purposes of enough stakeholders and maybe also suiting a very visible common purpose. Keeping food fresh, one example of the benefits of plastic mentioned, is difficult to argue against as a goal. But a focus on that goal suppresses alternative solutions such as increasing the accessibility (significantly including in terms of cost) of locally grown produce, or homemade (as opposed to processed) food. A more radical option, not arising from this discussion, would be to increase the ability of consumers to afford these more expensive non-plastic solutions.

This research is of course a product of the time and place in which it took place and reflects the interests of those partners who participated. Similar comparative research in the future with the same group or in other non-UK locations might provide interesting comparisons around the problematisation of the issues discussed. Yet notwithstanding the limited sample size, the research sheds interesting light on this issue. In microcosm, the research speaks volumes for the influences, or influencers, on the policy process. If you are not at least in the figurative room, you are not contributing to the collective imaginary.

Conflicts of interest

There are no conflicts to declare.

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Title: Slowing the loop: the role of grief and hope in building new economic spaces.

Kerry Burton and Joanne Smith[a]

In this paper we examine how civil society groups are tackling plastics within the South West region of England. We consider the drivers behind the rapid rise in 'plastic activism' in the region and how these groups contribute to wider considerations of the circular economy. We critique the techno-managerial conceptualisations of the circular economy and rational-actor approaches to nudging individual behaviours and call for more attention to be made to the relational, emotional, and affective connections that people have toward place, environment, and non-human beings. We consider the role of emotions and affect in driving new social practices that are, in turn, re-articulating local economic geographies through place-based responses to environmental concerns. We pose that, in response to feelings of grief and loss (for ecological decline and lost futures; see Head 2016), civil society groups are finding small spaces of hope that contribute to a plastics circular economy through new and reclaimed social practices that slow the loop.

Introduction

In response to successive scientific reports showing that the planet is undergoing a climate and ecological crisis requiring immediate and far-reaching action[1], environmental protests have called for urgent social and political transitions toward lower carbon societies. Public consciousness of the need to live within planetary boundaries and transition to a low carbon planet is growing. Public opinion has shifted since the IPCC report in 2018, which warned of dire consequences for human and non-human life if rapid action on climate emissions was not implemented imminently. More than 60% of households surveyed by the Centre for Climate Action and Social Transformations (CAST) in 2019 felt that there is now a high level of urgency to take action [2]. System transformation is being called for from both the bottom-up (environmental protests, NGOs) and the top-down (United Nations Framework Convention on Climate Change). The near global lockdown in response to Covid-19 has prompted governments and citizens to consider what directions social and economic recovery should take. Recent surveys by IPSOS MORI indicate that there is a an expectation that action on environment issues should be prioritized.

Resource management has come under increased scrutiny and levels of responsibility, as there is no longer any doubt that dominant systems of extraction-consumption-disposal threaten the social and ecological foundations of human survival. With natural resource extraction doubling since 1970 and continuing to rise [3] and the links between consumption and climate crises are now established [4], the shift toward regenerative systems is becoming more urgent. Within this, the circular economy has gained political and social backing as a system level approach that seeks to minimise the impact of production, consumption, and disposal by keeping resources within regenerative closed loops [5]. Although the role of governments and businesses are established, the role of place-based community initiatives in this system-level change is less clear. However, as we demonstrate here, place-based community initiatives perform a crucial role in slowing the loop, through social practices and diverse economies, and are key sites within the co-production of a more holistic circular economy, that encompasses social and environmental considerations.

Here, we discuss the possibilities of a circular economy for plastic through the lens of rural place-based initiatives. Through research undertaken across three predominantly rural and coastal counties in southwest England (Cornwall, Devon, Somerset), we consider the drivers behind a rapid rise in plastic activism (broadly understood), how this anti-plastic sentiment has motivated community action, and how the emergent place-based community initiatives contribute to wider considerations of the circular economy. Our research demonstrates the need for more focus on rural place-based initiatives, as sites of new social and economic practices and as change makers positioned between the individual and wider society. We pose that place-based initiatives challenge the top-down techno-managerial discourse of the circular economy, which, through their absence, presents the individual as a passive and rational bystander to wider economic systems [6] rather than a citizen with the agency to participate and change the status quo. We call for more attention to be paid to civil society initiatives and the agency of communities to facilitate new social practices that perform the economy differently [7] and with more circularity, and how these have the potential to underpin sustainable and inclusive rural development pathways. Following Head's work of grief and hope in the anthropocene [8] we also consider the role of emotions, affect, and place in mobilising and shaping pro-environmental behaviours and social and economic

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practices that rethink rural sustainable development through place-based community initiatives that are responding to environmental and social concerns.

The circular economy model of development has been posed as an effective way to address the environmental issues and create sustainable resource use that eliminates waste through closed loop systems. The circular economy has risen in prominence from a sustainable development concept to policy driver, being adopted by China, the EU, and Scotland. The practical emphasis of the circular economy is on closed loops, eliminating waste altogether by keeping all resources within a system of reclamation, use, and reuse [9]. In the UK this concept has followed two key models: the circle/loop, to keep resources in use for as long as possible, extract the maximum value from them whilst in use, then recover and regenerate products and materials at the end of each service life (see WRAP.org.uk) and the dual loop, two intersecting loops that keep resources in a continuous flow of technical and biological materials through the 'value circle' (see ellenmacarthurfoundation.org). Although moving away from the linear models of production and consumption is largely welcomed by many environmental movements, many of the underlying assumptions are grounded in techno-managerial approaches to social-technical transition, and narratives that seek to better manage resource systems through top down technological fixes. Top down conceptualisations have focussed on better designs, recoverability through incorporating reuse of resources through increased use of recyclable materials, and schemes for companies to recapture materials through end of product use recovery (such as return schemes). Within the urban context the circular economy is gaining traction as a place-based development model, with London and Bristol actively working on strategies to become 'circular cities'. As our research shows, the diverse social and economic practices of rural place-based initiatives are adopting expanded circular economy principles, embedding an ethics of care into an otherwise technical discourse, demonstrating the importance of emotional and affective responses and attachment to place.

Place-based initiatives have gained currency within sustainability transitions. Place remains a contested concept, associated with spatial identities that perform exclusion through a sense of 'rootedness' and 'fixity' [10]. Place attachment and perceptions of what is 'out of place' in the rural have sometimes shaped negative responses to pro-environmental development (particularly windfarms) through NIMBYism [11]. However, recent research has also demonstrated that place-attachment can also be a driver of pro-environmental action [12]. Work on 'progressive localism' also demonstrates that actions are being shaped by outward facing commitments to distant others, rather than inward facing essentialisms [13]. Within the growing emphasis on socioecological threats at both local and planetary scales, place is increasingly understood, by both academics and inhabitants, as relational, dynamic, and more-than-human [14]. The place-based initiatives we examined understood place through predominantly outward facing perceptions, but where inward facing representations were sometime also presented. Here, most of all, place was understood as a starting point - as Gibson-Graham illustrate, when trying to change the world, start where you are [15].

There is now consensus (social, scientific, and political) that we are in a time of climate and ecological crisis and, as Solnit has shown, civil society experiments with acts of collaboration and experimentation often emerge in times of crisis [16]. Hope drives people forward, as the only alternative to surrender [17]. Arguably, hope engenders emotions, affect, and rationality; as Roeser illustrates in relation to disaster management we need emotions in order to be practically rational [18]. Although fearful and painful emotions, such as those generated by increased exposure to images of ecological harm or the impacts of extreme weather events, are sometimes thought to inhibit the capacity to act [19, 20] , the recent surge in environmental activism demonstrates that fear, anger, sadness, and hope can move people to take action, both on the street and in communities. Increased visibility of climate crisis and ecological decline has deeply affected many people, with visible outpourings of loss akin to grief for the futures lost to unfolding events and processes [8]. In response to high profile campaigns and media attention focussed on the impact of plastic on the non-human world, the material has emerged as a key site of passionate politics [21], with political (protests) and social (community initiatives) responses.

Plastic has shifted from hero to villain in a short number of years. Its popularity was driven, in part, by emotions and affect, as plastic, particularly drinks bottles made from PET, started as a marketing hit [22]. Cheap and convenient products have come under increased criticism, as the socioecological costs of plastic waste and pollution have become better understood, and plastic is now one of the most contested materials on the planet. Campaigners for plastic reduction have focussed on three core issues: marine pollution, climate change, and environmental justice. Plastic production is rapidly accelerating, with the packaging, construction, and fashion industries as the primary users. Since its introduction in the 1950s, an estimated 3.8 billion metric tonnes of plastic have entered the environment and this waste is also accelerating. More than 3 million metric tonnes of plastic are thrown away each year, of which 79% of is discarded, less than 9% recycled and 12% incinerated [23, 24]. Plastic waste from the UK is a global problem, with large amounts exported abroad for processing. Investigations into the global trade in plastic waste found that following China's ban on plastic waste imports many UK councils had been exporting domestic waste (including lots that had been sorted for recycling) to countries with weak or non-existent regulations, leading to calls from publics, government ministers, and NGOs for action to be taken. However, as O'Neill examines, plastic waste is a global economy, with complex political economic chains creating a waste picking industry that many of the poorest communities are reliant on for their livelihood, at the expense of human (including their own) and ecological health [9]. In addition, the Centre for International Environmental Law's 2019 *Plastic and Climate: the hidden costs of a plastic planet* reports that production and incineration creates 850 million metric tons of greenhouse gases a year and, if plastic production grows as predicted, this will rise to 1.34 $GtCO_2e$ over the next ten years (to 2030). In response to the growing visibility of these global issues, local action on plastic, through individual actions, like product avoidance, and community initiatives, such as sharing schemes and reuse networks are gaining in popularity.

Methodology

The research addresses two major gaps in current research on the circular economy in general and plastics more specifically: the role and contributions of community-level initiatives and the performance of circular economy practices in rural settings. Our aim was to examine the motivations, actions, and impacts of community initiatives within the rural and coastal areas of the South West region. Research was undertaken in 2019 and 2020, to examine regional initiatives as part of the EPSRC funded ExeMPlaR project. We examined community initiatives that were place-based and that openly claimed to be tackling plastics as either the primary or subsidiary aim of their activities and made specific links to circular economy as a goal or influence. To examine the performative dynamics of community initiatives, the methodology takes influence from community economics, incorporating participatory workshops, participant observation, and mapping typologies of individual actions and emerging social practices. To better understand how social practices are being made, reclaimed, and undone, we look to Shove et al.'s three core elements: 'meanings', 'competences' and 'materials', examining motivations and values, shared know-how and practical intelligence, and objects and infrastructures [25]. Stakeholder workshops were held early in the project (Feb and July 2019), adopting participatory methods to understand what was happening in the region, where it was happening, and who were the key constituents of networks. Using network mapping methods, influenced by social movement research, this data was used to create an interactive topographical map of where initiatives are taking place, creating a performative space that people and initiatives can both view and contribute to. The use of social media within mobilising and co-production was also researched, using discourse and content analysis of text and images. These elements formed the basis of two case studies, the first examining major regional networks and how they mobilise and shape practical action, followed by an examination of community initiatives that focussed on the key circular economy principles, reusing, repairing, and sharing, to better understand social practices.

Findings and discussion

The emergence and networking of place-based initiatives in Somerset, Devon, and Cornwall.

Place-based initiatives to deal with waste have been present in the environmental action landscape of south west England since the 1990s, with plastics emerging as a cited issue within the last decade. Most of the place-based community led initiatives were

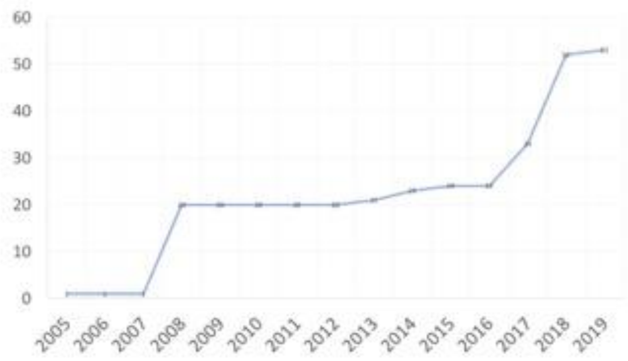

Figure 1: *Emergence of place-based initiatives in Devon, Cornwall, and Somerset*

in small to medium sized rural and coastal towns (with populations of between 5,000 and 25,000), many of which provide local services to a wider area of small villages. A couple of the initiatives started in the 1990s, with a significant minority emerging between 2007-2009 and the majority (70%) of groups starting since 2017 (see Figure 1). All the initiatives are re-conceptualising the relationships between humans and nature, through acknowledging the relationality of place and global processes, and restructuring place in order to minimise destructive relationships and promote generative ones. Two core networks, both initiated and based within the South West, shape the form and function of actions, through very different approaches. The recent initiatives were almost all affiliated with the Surfers Against Sewage 'Plastic Free Community' scheme; the dominant discourse was that of marine pollution (as we discuss below) and actions aimed at individual and institutional behaviour change. The initiatives that were established prior to 2017 approached the issue of plastic through discourses of waste and resource management and were those whose actions were grounded in systemic change, through social practices and local infrastructures. Most of the established initiatives are affiliated to the Transition Towns Network. In some locations (e.g., Penzance, Totnes), both initiatives are present. Both the 'Plastic Free Community' initiative and those linked to the Transition Towns Network are of interest here, as we understand these networked groups as bringing together multiple civil society and local government stakeholders to create local innovations that perform the economy differently and slow the plastics loop. Both networks name the circular economy as a guiding model and facilitate practices that, we argue, contribute to the circular economy by slowing the loop including **avoid** or **refuse** campaigns, **reuse** initiatives, **repair** workshops, and **sharing** schemes. Although the two networks often overlap, it is important to acknowledge their different trajectories.

Across the three counties, the more established groups were part of the Transition Town Network (and movement) and many had links as far back as the Local Agenda 21 (LA21) policy initiative. This process emerged through the United Nations Conference on Environment and Development (UNCED), or Rio Earth Summit, in 1992 and devolved responsibilities for sustainable development to the local scale, encouraging local authorities, and in turn citizens, to 'think globally, act locally'. As

Barr [26] explains, the significance of affording community and local level participation saw a cultural shift in how citizens contributed to sustainability action, with local authorities facilitating volunteer working groups, usually around food, energy, waste, transport, and biodiversity, and supporting local action through small grants. Many working groups also contributed to local authority strategic plans, though others note the slowness of LA21 processes and the failure to enable participation beyond white middle-class groups [27]. When LA21 was superseded by other local authority policy frameworks, the emerging Transition Town movement offered a new mode of civic participation for those involved in place-based groups. Starting in Totnes, Devon, in 2008, the Transition Town model initially attached itself to the concept of 'peak oil' and working groups (again focussing on food, waste, consumption, and transport) created place-based pathways to end oil dependency. Critiqued for actively taking a post-political standpoint [28] the TTN has developed into a framework for tackling climate change through low carbon living, through an emphasis on new socio-economic practices that create system change from the bottom-up and has an international network of Transition Towns (transitionnetwork.org).

The more recent wave of groups, emerging from 2017 onwards, are mostly affiliated to the 'Plastic Free Communities' scheme managed by marine NGO Surfers Against Sewage (SAS). SAS have a strong presence in the South West, starting as an environmental campaign group who successfully mobilised surfers (and others) to protest and lobby against bathing water quality and the practice of raw sewage openly entering the sea around the UK [29]. Starting in Cornwall in 1990, the organisation has grown in membership, scope, and influence over the last three decades, gaining, with the headquarters based in the Cornish town of St Agnes. SAS have been at the forefront of UK campaigning against plastic pollution through their popular 'Plastic Free Community' scheme (sas.org/plastic-free-communities). The Plastic Free Communities (PFC) scheme adopts a similar model to that of the Fair Trade Towns movement, whereby place-based groups can gain accreditation based on completing a checklist of actions and setting goals that combine ethical consumerism with community consciousness raising. At the time of this research more than 30 South West groups had received accreditation and more than 100 had pledged to work toward certification. The steps to achieving accreditation and the Plastic Free Community certificate are based on the size of community. For example, a town with 10,000 residents would need to get five businesses to eliminate or replace three types of single use plastics (SAS recommend bags, straws, sachets), get the local council to commit to tackling single use plastics, and get key organisations (such as schools or church groups) to pledge to take action.

Mediating the matter of plastics and reframing nature-society relations.

Environmental action movements have recognised that social media is a crucial tool for mobilising action [30]. Prior to ubiquitous access, the internet had already become a key organising tool for environmentalists around the world, raising consciousness and building political force [31, 32] . Now, with almost universal access to a wide range of real-time information sharing platforms, the growth of social media has created new species of social movement [33]. The speed at which information can reach a global audience through social media, where participation on these platforms amplifies and elevates issues through the ordinariness of liking, tagging, and sharing. Interactive media platforms have shifted the human-nature dynamic within conservation, as people increasingly feel part of the process through following and liking [34, 35]. Moreover, the co-production spaces opened up by social media also shape the form and function of journalistic reporting around contested resources [35]. Following the screening of the BBC natural history documentary series *Blue Planet II,* in November 2017, which included scenes of plastic debris being played with and consumed by marine life, including whales and Dolphins, there was a considerable rise in social media calls for action to ban plastic. In the weeks following the screening, a proliferation of political (anti-plastic protests), economic (boycotts of plastic products), and social (community initiatives) responses were facilitated through social media. An exponential rise in mainstream media attention on plastic pollution followed [36] as did a surge in plastic activism, including NGO mediated actions to return packaging to supermarkets. The 'Blue Planet effect' is cited by the supermarket Waitrose as influencing 80% of its customers to reduce plastic consumption. The findings led Waitrose (and other supermarkets) to experiment with new practices (dry food dispensers, for instance) and alternative materials for packaging. The Glastonbury Festival 2019 was also promoted as a plastic free festival, with restrictions on single use plastics and innovations including water bars. Whilst elements of recent changes can be understood as a new form of greenwashing, that Hobson calls 'circular washing' [37].

As our research illustrates, the increase in place-based groups also soared in response to the program and the debates it opened, mobilising widespread support among a diverse constituency. A small number of the established place-based initiatives had static websites, with no mechanisms for participation from anyone other than those managing or administering the webpages. For most of the initiatives that emerged following the 'Blue Planet effect', Facebook was the primary online space, which was used to recruit new members, share news items and photographs, promote upcoming events, and share personal and group level action. For many groups, particularly those affiliated to the plastic free communities initiative, social media is the main platform for information exchange and networking within and beyond the locality of practical action. Images of animal entanglements and plastic debris collected on beaches would often be circulated across more than one Facebook group. These images and the comments with them are reminiscent of early understandings of waste, as 'matter out of place' [38], with the pristine and natural landscape being an un-natural place for plastic. The coast was, in particular, often presented as a place that should be safe for non-human beings, a narrative that re-writes a past and present that is reliant on the sea as a site of killing (fish).

Moving plastics into broader environmental discourses has resulted in growing instances of contestation, particularly in relation to the eco friendliness of alternative products, such as cardboard packaging having a higher carbon footprint than plastic or aluminium drinks cans being more carbon intensive to recycle than plastic bottles. The ecological credential of bioplastics were a major site of discussion and contestation, with many posts promoting alternatives such as compostable packaging being contested on grounds of ecological and biological evidence and whether these items are necessary in the first place. These discursive battlegrounds are indicative of what McLean refers to as the 'ordinariness of environmental dilemmas' [30]. Contestation raises some important issues about social movements in online spaces. Although most discussions and arguments were illustrative of a highly informed constituency, there are overlapping issues within the organisational structure of such open platforms. Competing discourses can generate some important spaces of generative friction, as conversations can turn into actions or new co-produced understandings. However, online spaces of contestation around complex issues frequently can't be resolved through self-organising small groups, who have minimal input of external expertise or conflict resolution capacity. Through these ordinary and simple interactions, that don't necessitate any physical commitment beyond the phone or computer, the viral spread of images and stories can garner affective and emotional responses.

Performing the circular economy through place-based initiatives.

As others highlight, there is no natural basis to our current economic system based on financial growth and there is no reason that human and environmental wellbeing shouldn't be prioritised [39]; the economy is not something distant or abstract from everyday lives, it is the outcome of the everyday decisions we make. Recent projects have documented how community initiatives are transforming cities around the world and reconfiguring economic relationships through a range of social economic practices, including sharing and community economies that position environmental and social wellbeing at their heart [40]. In 2020 the municipality of Amsterdam has adopted Raworth's doughnut model as a foundation for rethinking the city through a wellbeing economy framework. While the rural is often represented as the slow moving, low tech counterpart to the smart and progressive urban, our research illustrates that it is also a dynamic space where diverse economies are contributing to wider circular economy systems. As demonstrated through our discussion on the mediating of plastic and the reframing of place (above), rural and coastal inhabitants also recognise that place is not a static location where we work and/or live, but a relational space, the product of global processes where human and non-human wellbeing is interwoven. The place-based initiatives that we have examined are all acting with both the local and global in mind; attentive to social and environmental wellbeing in their immediate surroundings and global issues such as marine pollution, climate change, and natural resource management.

The place-based initiatives we examined didn't position themselves beyond the state (unlike most protest movements) but did, on the whole, operate beyond its neoliberal rationalities. The circular economy was approached as a framework, rather than model. Within the framework, a number of diverse economies are practiced. Within our research, we have focussed on avoidance, reuse, sharing, and repairing, understanding these as core social practices that contribute to the circular economy, by slowing the loop, and to community capacity to thrive. Two sets of initiatives are rising in popularity in the study area: sharing libraries and Repair Cafés.

The study areas has a growing cohort of sharing libraries, including those with their own premises, those situated within existing community centres, and the world's first mobile library of things, which will serve rural towns in Devon. A number of additional groups are also in the process of setting-up sharing libraries in at least four additional communities. Sharing libraries aim to meet the needs of users through an acknowledgement that the value of many household items (electrical, DIY, leisure, gardening etc.) is in the service they provide, services that are often not needed on a daily basis. Sharing schemes provide a wide constituency of people with access to the services that products enable without the need to own them; for instance, the service of cutting the lawn, without the financial cost and storage space needed to own a lawn mower [40]. A focus on service provision rather than ownership is increasing viewed as an environmental issue, by reducing resource flows, and a social wellbeing strategy, by increasing people's capacity to access the services that products provide at affordable financial cost.

The study area also has a growing number of regular (usually monthly) Repair Cafes, where skilled volunteers will endeavour to fix household items, usually ranging from electrical to clothing, for a donation to the initiative or a small charge to cover replacement parts. The aim is to keep items within use for longer, avoiding the need for new purchases. Repair Cafés are internationally networked and have been important actors within campaigns against product obsolescence and new laws on the right to repair. Again, these are driven by an ethics of care for both environmental and social wellbeing.

Conclusions

Our research addresses a lack of focus on the circular economy practices of rural place-based initiatives and the dual possibilities of bottom-up organising and progressive forms of localism. We have shown that there are social and economic practices being made, unmade, and reclaimed, that can contribute to a circular rural and offer inclusive forms of sustainable development. We have shown that place-based community initiatives are contributing to a wider regional circular economy through social practices that slow the loop - reducing the need to buy products and helping to keep items in use for longer. Despite the prevailing techno-managerial emphasis of circular economy models and narratives we argue for importance of recognising the role of emotions, affect, and place. Diverse economies are being motivated by both rational and emotional and affective responses to local and global ecological and social concerns, reconfiguring and expanding circular economy discourses to acknowledges ideas social wellbeing in addition to managing resources.

Conflicts of interest

No conflicts of interest.

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Session 5: Supply Chains & Behaviour Change

A Vision for Plastic Circularity in the UK: One Bin to Rule Them All

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Plastic is a remarkably versatile material that has transformed our healthcare, food security and built environment industries. However, plastic is devalued by its description as waste and further complicated by the complexities and inconsistencies on how we process the material once disposed. Reducing or eliminating leakage of plastic into the environment could be achieved by simplifying decisions for consumers with a consistent message: place all plastic-like objects into one bin. Modernised waste management systems can then prioritise retaining value with advanced sorting through reuse, mechanical recycling and chemical recycling pathways. Reducing plastic leakage is tightly linked to creation of a circular economy of plastic. We illustrate how standardisation across the supply chain, investment in infrastructure, value creation decision making and collaborative business models must work in concert to deliver change. Increased recycling is essential to promoting this circularity but is hindered by limited infrastructure, polymer diversity and widespread consumer confusion over plastic recycling. Sorting based on polymer type is too limited, instead we advocate sorting based on the pathway that best retains value. What should be reused, mechanically recycled or chemically recycled is determined by open rules pre-set according to this retained polymer value. Barriers preventing the implementation of this vision were investigated through 23 semi-structured interviews with industrial and policy partners from across the supply chain. We argue that the vision is not only achievable but essential for the future of waste management. Agreeing cooperation between competitors across and along the supply chain and innovating around these contestations will likely be the greatest hurdles to implementation.

1. Context

Creating economic and societal value from material circulation requires engagement and integration across academic disciplines, sectors (academia, industry, government, civil society), resource flows, and dimensions of value (national security, ecology, economy, wellbeing, governance), all while acknowledging the possibilities and limitations of our material world. This is especially true of plastics as a resource flow, as the ubiquity and diversity of their use and visibility is matched by the tunability of polymer functionality, durability and integration into composites and multi-materials. This necessitates a coordinated, interdisciplinary approach to developing interventions that focuses on retaining, defining and delivering value through circulation.

A vision for the future of such a system, co-developed with cross-sector stakeholders, is captured by the moniker 'One Bin to Rule Them All'. This imagined future hinges on the hypothesis that eliminating plastic leakage into the environment starts with making compliance straightforward for consumers. This vision reflects research that consumers are confused about proper plastic recycling practices in the home.[1] As we illustrate, this confusion can only be overcome by there being 'One Bin' into which all plastic-like items should be placed. The moniker's ability to convey the substance of the project in a light-hearted way has proved invaluable in building stakeholder relationships, although the conceptual implications are far wider than consumers and households.

The study examines the validity of the One Bin concept. The initial vision (Figure 1) recognises the need to eliminate the three main methods of plastic leakage (landfill, commercial incineration and littering) through three main circular cycles (reuse, mechanical recycling and chemical recycling). Together these form an agenda for the plastic circular economy. Creating value in these plastic resource flows will incentivise supply chain members to change. This paper focuses on the consumer sector due to the prevalence of single-use plastic items and the pressure on the packaging sector, by both public and policy, to reduce such packaging. However, and significantly, our future efforts will seek to extend the agenda across all relevant industries.

Concern about plastics in the environment is growing. The UK Plastics Pact has been formed with member companies responsible for over 80% of the packaging sold through UK supermarkets.[2] Following the EU's Single Use Plastic Directive, WRAP has listed 8 products members are expected to remove from packaging by the end of 2020: some are trivial, such as plastics straws, and some significant, such as any use of poly(vinyl chloride) (PVC) and polystyrene (PS).[3] Indeed, no comprehensive vision across the supply chain has been set out: only specific, tightly defined, and indeed straightforward problems are being tackled.

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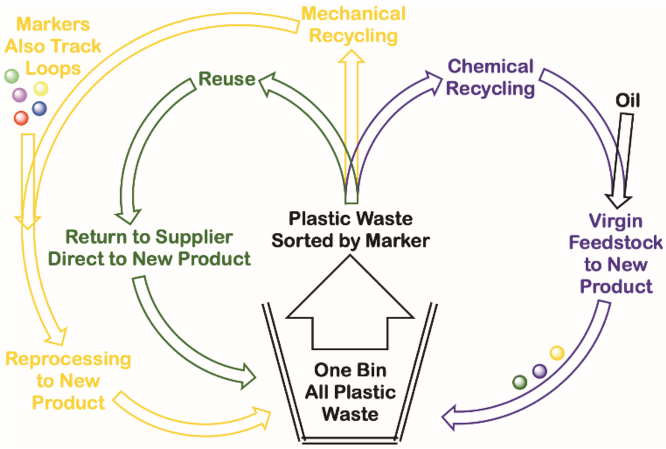

Figure 1. One Bin To Rule Them All.

'One Bin' aims to rectify this deficit by recognising that post-consumer plastics sorted by polymer have a value almost irrespective of the polymer. Without a subsequent realisation of value, limited sorting and recycling capacity will not be addressed. The scale of the connected problems is shown in Figure 2. Landfill, littering or incineration is the fate of 76% of rigid plastic consumer packaging,[4] with incineration recovering only 5% of the polymer value in energy the best-case scenario.[5]

The One Bin vision strives to retain plastics in their highest value condition,[5] promoting sorting based on value instead of polymer type. It thus aligns with the European Strategy for Plastics in a Circular Economy.[6] The overall rationale for a circular economy,[7] its wider issues[8] and morality[9,10] are well established, as is the need for sector and geographic specificity.[11,12] Most relevant, however, is the explicit demand for newer business models[13,14] and importance of consumer perspective and understanding.[15-17] From our specific perspective, any One Bin system change must retain the perspective of the consumer, and the need for improved compliance at the core.

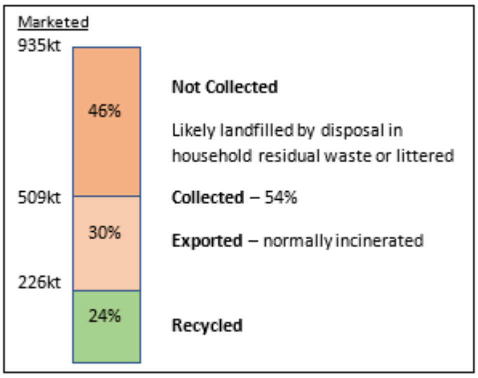

Figure 2. Disposal of Rigid consumer packaging in the UK, 2017. Modified from WRAP.[4]

Compliance is improved by simplification of the process. UK household waste collections are the responsibility of Local Authorities (LA) with variants of multi-bin collection systems creating confusion. Most LAs collect all plastic bottles (predominantly composed of polyethylene terephthalate, PET, and high density polyethylene, HDPE), some collect all rigid packaging plastics (including pots, tubs and trays) while very few collect plastic films. With 391 LAs and 39 different collection regimes[18] consumer uncertainty degrades compliance, especially when overlaid with differing rules for different settings (e.g workplace, leisure). Research on why and whether households recycle[19,20] lacks complementary work on compliance and contamination. Within circular economy debates there is little coverage of how plastics are recycled at home. Behavioural literature suggests that recycling is highly normed[21,22] although there is limited work on the role of household norms in decision making.[23] There is minimal agreement on the influences over recycling behaviour[24] and little or no work on whether consumers are confused by product packaging. This all results in a stark reality: of the rigid plastics supplied to the market only 54% is collected.[4] This highlights the challenges of improving circularity through behaviour changes alone.

It is this combined contamination and collection challenge that makes it difficult for material recycling facilities to produce consistent high-quality recyclate, having punitive impacts on waste management contracts. This lack of feedstock is coupled to an unprecedented demand, as using recycled inputs is easier than changing the business model to incorporate reuse or remanufacture.[25] Government facilitated industrial symbiosis projects have poor rates of success.[11] Whilst the EU urges key players to work together, and technical barriers are not regarded as the main issue, issues of culture and cooperation are significant.[6,8] The lack of standardised traded plastic wastes, considered a prerequisite by some authors for investment into reprocessing capacity[9,12] further complicates solutions. Any business needs reliable, standard inputs. Without active waste markets, individually negotiated sources of supply create precarious positions unlikely to be an attractive investment.

Focusing on the four key areas of standardisation, infrastructure, value creation and collaborative business models, we illustrate how circularising plastic waste is urgent, necessary and achievable within the UK plastics economy. From standardisation (of polymers, of systems for collection and processing, of recyclate quality), to infrastructure enabling better sorting, to supply chain transparency, and collaborative business models, 'One Bin' adoption demands value creation for each member of the complex supply chain as a driver for changing practices.

2. An Evolving Regulatory Framework

Five 2019-20 UK-based consultations will help shape essential regulations that enable or disable change: Consistency of collections (England only), plastic packaging tax (UK), extended producer responsibility (UK), deposit return schemes (England, Wales & NI) and broader circular economy strategy (Wales only). This illustrates the diversity of governance approaches hindering creation or application of a standardised UK-wide solution, but also the recognition that regulation is needed in plastic waste management.

These evolving regulations are also a lens through which to examine 'One Bin' and also highlight how important it is to inform on this process. The English government may mandate recycling requirements for English LAs by 2023; the hope is that Scotland, Wales and NI follow this lead. Cost may be a major issue preventing standardisation of bin colours, both in replacing bins and collection infrastructure (trucks, MRF equipment) if the methodology is standardised. The UK government has proposed a £200/ton Plastic Packaging Tax from April 2022 on any packaging containing less than 30% recycled content, irrespective of polymer, availability of recyclate, potential for higher incorporation, or loss in material performance when meeting targets.[26] This supports demand for recyclate and creates value for it, an essential feature of 'One Bin'. Extended Producer Responsibility scheme (EPR) will likely launch in 2023,[27] with the producer responsible for the full cost of managing the packaging produced at the end of its first life, supporting design for recycling and the use of easily recyclable materials, key tenets of 'One Bin'. This is supported both by respondents to the government and our partners.[28] Operational details are unclear, but it is hoped that all or part of the funds raised can be invested in infrastructure to provide higher quality recyclate,[29] as needed to enable 'One Bin'. Lastly, The UK and Scottish Governments are also planning to set up Deposit Return Schemes (DRS) for plastic and glass drinks bottles, whereby each bottle sold carries a reclaimable deposit of 20p (£0.20).[30,31] This is tangential, or even detrimental, to One Bin: we and our partners are concerned that DRS removes the one profitable plastic household waste stream which is currently well sorted and recycled through MRFs (PET bottles: 74% collection rate).[32]

3. Methods

Project partners were recruited through the framework of the Rethinking Resources and Recycling consortium at the University of Manchester, building from existing industry contacts, strategic university partners and panel or plenary lectures at trade events and conferences. The initial 'One Bin' vision, as described above, evolved from an initial back-casting exercise. A series of 23 semi-structured interviews examined partners' different perspectives, in particular examining the potential challenges they felt One Bin was likely to face. Partners were deliberately recruited from disparate parts of the supply chain, from thermoformers, tagging specialists, retailers, fast moving consumer goods retailers, a major waste processing organisation, local government, PET and PVC recyclers to a waste compliance SME. Importantly, each presented a different view of the key issues which needed resolving. Together the partners presented a comprehensive overview of the packaging supply chain. Sections that had significance for either the individual partner and/or the wider industry were summarised or transcribed, with key points and themes extracted from the longer text. This output provided a series of *points of agreement* across partners together with four areas, or *contestations*, that required further exploration.

The second stage consisted of a full-day workshop involving 13 of the partners. This event confirmed areas of agreement and explored contestations to co-create an ideal circular plastics future. In particular, four open questions framed these conversations: (1) On the standardisation of materials: If we agree that standardisation is a good thing, what standards do we need? (2) On sorting and technology: What do we need to do to ensure that Pots, Tubs and Trays are recycled? (3) On value creation: If it were possible to create a marking system to enable separation of packaging by polymer, is this enough on its own to generate investment in the sorting infrastructure by MRFs and in marking of products by brands and retailers? (4) On pilot trials: If we have an embryonic method of creating value (a marking process being one example), what would a trial be designed to prove? The "World Café" discussion format[33] split partners across four tables with paper tablecloths. Teams wrote their contributions to one question on each tablecloths, triggered by prompts, facilitated by an academic at each table. After ten minutes teams rotated to the next table. Newly arrived groups could see the previous contributions and add or comment as they wished. After four rotations the collected thoughts were fed back to the whole meeting by the table facilitator.

The partners were then split into four different groups for a back-casting exercise where participants devised their ideal One Bin future, detailing intermediate steps necessary to reach the endpoint. Starting with the ideal future helps to avoid extrapolating current trends or assumptions.[34] Starting with their envisaged circular plastics goal in 2030 or 2040, the groups had to isolate specific actions to be implemented by specific times to realise their endpoint and record on an A1 size pre-printed sheet of timescales and Action Categories (Figure 3). The aim was to uncover hidden key steps and ideas that might otherwise be missed.

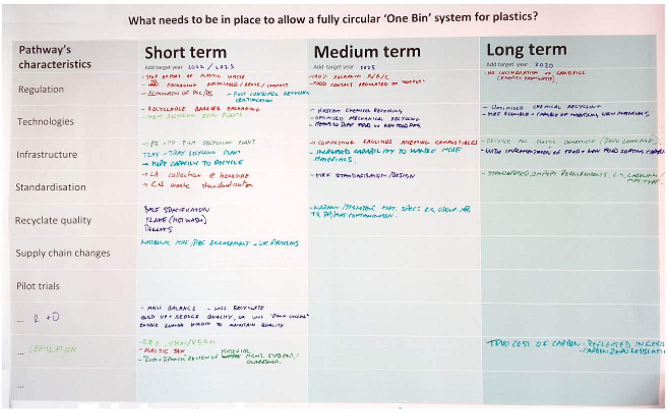

Figure 3. An illustration of a completed back-casting exercise worksheet.

4. Results and Discussion

4.1 Standardisation. Our findings confirm that to realise a circular economy of plastic standardisation is crucial across the whole recycling sphere. This applies throughout the supply chain, from bin collections to polymer grades, data, sorting techniques and machinery. Standards need to be open, UK wide, accessible, unbiased and owned by an open stakeholder group. Manufacturing criteria should determine standards and be polymer and sector specific, covering performance criteria, contamination limits and recycled material content.

The initial hypothesis of 'One Bin' that customer confusion causes reduced collection levels and increased contamination was supported by partners. National operating standards for MRFs (and PRFs – Plastic Recovery Facilities) are perceived to be important, including standards on recyclate quality that would necessitate infrastructure investment. Several partners agreed that further gains could be made if packaging polymers were standardised grades of polymer. Currently each manufacturer can use any grade appropriate to functionality, and indeed many decisions are driven by legacy instead of science. Standard grades improved recyclate consistency and allows closed loop processing. An emerging idea was to further standardise on design, such as permitting only three standard shapes and sizes of PET trays for food use throughout the UK. While improving recyclability, it also opens up new possibilities for reuse, subject to material choice and an assessment of water and energy use.

4.2 Infrastructure. Our findings confirm that the UK does not generate enough recyclate to fulfil market needs for PET, HDPE or PP and that the infrastructure does not exist to do so. Partners with a packaging focus recognise the need for a machine-readable marking system enabling high-speed sorting. This would be transformative for a reachable target like food grade polypropylene (PP). By law, recycled plastics incorporated into new food containers must have originated from containers already used for food use. Identifying food grade PP from non-food grade PP in a MRF is currently impossible, causing most food-grade PP to be incinerated or at best downcycled. Sorting based on value instead of polymer backbone would identify food grade PP and create value. Partners agreed that this is not a technology issue – there are available systems – but a problem of supply chain cooperation, confirming earlier findings[8]. It highlights that One Bin - or any solution - needs to demonstrate value creation across the supply chain to promote change and must be supported by regulation.

4.3 Creation of higher value recyclate. The need for higher value recyclate is crucial in creating a circular economy for plastics. Interviewees estimated that bales of sorted plastic from MRFs are 70% on-target material on average. Higher qualities are facilitated by machine-readable marking to reduce contamination levels, increasing bale value. Most partners agreed that the existing Packaging Recovery Note/Packaging Export Recovery Note (PRN/PERN) system designed to incentivise plastic recycling is not fit for purpose. This mechanism incentivises exporting unsorted plastic rather than sorting and retaining value in the UK, as PRNs and PERNs have the same value per ton.

4.4 Collaborative business models across the supply chain. Using a machine-readable marking system to create value involves supply chain cooperation around a single agreed system. Marking would be undertaken by manufacturers or retailers while benefits from higher value product accrue to MRFs who sort and sell it, necessitating a return on investment for those earlier in the supply chain. Value could be transferred from MRFs to a retailer by reporting the volumes of individual products recycled, reducing their expected liabilities under proposed EPR legislation and giving confidence that their brand has ensured the product is recycled. There is additional marketing value if the recycled item can be linked to customer data. Collaborative business models are thus inherent to the 'One Bin' vision.

4.5 Enabling interrelationships. As we have shown, the requirements of system change to realise a circular economy of plastic in the UK are split into four over-arching, interlinked themes: standardisation, infrastructure investment, value creation and collaborative business models. Partners have also identified specific sub-areas, such as improved mechanical recycling, design for reuse, economically viable chemical recycling and regulatory changes, which serve as enablers for change.

Although consumer behaviour in the home is recognised as crucial to reducing contamination of MRF inputs,[1] and a consultation on consistency in England has been undertaken, the remaining key factors that will promote real change are not central to the UK government vision. Our research suggests that partial consistency, particularly if the other national governments (Wales, Scotland, Northern Ireland) do not align, will have a limited impact and risks locking us into the current disjointed system.

The overriding need for standardisation to create greater volumes of better sorted, higher value recyclate suggests that a shared, UK-wide agreement on workable solutions is needed. We have highlighted interdependencies between supply chain members, and how progression to higher UK recycling levels involves greater cross-industry cooperation. This is not facilitated by current competition law. Alignment across the supply chain must be married to alignment across the British Isles, translating to global cooperation in the future. There is significant concern that upcoming changes to PRNs/PERNs, and the establishment of EPR measures, will disable rather than enable necessary change, and bringing in multiple measures simultaneously asks for unexpected and unintended consequences. The genuine appetite for our partners to improve their sustainability must not be curtailed by legislation.

The back-casting exercise revealed what actions partners felt to be essential in the medium term (ca. 5 years) if the 'One Bin' vision of zero plastic waste leakage into the environment is to occur by 2030 to 2040. These include standardised kerbside collections, specification of bale outputs (sorted but unrecycled plastics) from MRFs and an end to exports of unsorted plastics. They anticipate impact from EPR regulation from 2023. Additionally, the next five years need to prove the roles of both a digital marking system and chemical recycling in a modern waste management system. This necessitates trials of sub-economic pilot scale versions of these innovations, with both required to become mainstream in a 10-year timeframe.

5. Conclusion

Delivering a 'One Bin To Rule Them All' vision to eliminate plastic leakage into the environment through controlling reuse, mechanical and chemical recycling is tightly linked with enabling a circular economy of plastic. Sorting by value instead of polymer to increase UK plastic recycling volumes can be delivered. This requires immediate action across four supply chain areas: standardisation, infrastructure investment, creation of higher value recyclate and collaborative business models. We do not try to suggest that ongoing initiatives by many organisations are misguided: 'One Bin' seeks to provide a more ambitious vision of an overall framework within which progress can be framed.

Cross-supply chain standardisation (coherent bin collection, fewer polymers, consistent marking, standardised recyclate bales) and new recycling data must be produced using open standards and not controlled by one section of the supply chain. Decisions made on reuse, mechanical recycling or chemical recycling must be made on a basis that is transparent to all. The plethora of regulations to be introduced across the UK over the next three years is essential but also bears the potential for missteps. 'One Bin' necessitates a harmonised national solution to plastic waste sorting, and such an intervention is supported by this research and a surprisingly aligned industry supply chain. The premise that consumer confusion over recycling precipitates low collection rates, while widely believed, remains untested. The interdisciplinary design of the research, involving material scientists, economists and social scientists, has been crucial to the process, with its evolution from polymer chemistry to one querying household practice and collaborative business models refining the questions we ask. Importantly, chemistry may determine the recycling approach (mechanical or chemical), but it is the sustainable system that creates value.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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Behaviours, influences and interventions to reduce plastic waste: a systematic review and meta-analysis

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The accumulation of plastic waste represents a growing threat to both human and environmental health. Solutions to the plastic waste problem rely, in part, on changing behaviour – addressing overconsumption and poor waste management. This systematic review aims to a) identify and categorise key behaviours with respect to plastic waste, b) identify influences on behaviour, specifying barriers and enablers in terms of capability, opportunity and motivation (i.e., the components of the COM-B model) and c) identify effective behaviour change interventions, coding these into intervention types as described by the Behaviour Change Wheel, and component techniques from the Behaviour Change Techniques Taxonomy. By so doing, the review will provide a behavioural analysis of the plastic waste problem, inform future behaviour change interventions, and identify areas for further research aimed at understanding and reducing plastic waste.

Introduction

The accumulation of plastic waste represents a growing societal threat. It has been estimated that over the last six decades, 8,300 million metric tonnes of plastic have been produced[1]. Through inappropriate waste management, these plastics have made their way into the natural environment where they represent the most abundant litter material, accounting for 100% of floating litter[2]. Aside from the widely documented environmental impacts, such as risk of entanglement and ingestion of plastic by fish and birds[3,4], plastic particles and fibres have been identified in our tap water, beer, and salt[5,6] where the risks to human health are yet unknown. If our current plastic consumption and disposal trends continue, it is estimated that by 2050 an additional 12,000 million metric tonnes of plastic waste will be in landfill or littered, contributing to further environmental degradation[1].

Given the above, eliminating plastic waste is understandably high on the global sustainability agenda[7]. However, eliminating (or even reducing) plastic waste will require wide-scale system changes and a shift from a linear to circular plastics economy[8]. Circular systems keep plastic flowing around a 'closed loop' system where products are re-used, re-purposed, recycled, and recovered, rather than discarded after single use[9]. Achieving this shift to a circular economy is, in part, reliant on changing consumer behaviour (i.e. addressing overconsumption and inappropriate waste management). Widescale changes in consumer behaviour will, in turn, rely on actors across all levels of the plastics system (e.g. producers, suppliers and disposers of plastic) also changing their behaviour. To change behaviour with respect to plastic waste, the behavioural sciences offer a multitude of theory- and evidence-based principles that can aid the intervention development process.

With this in mind, a review of factors associated with behaviours leading to consumer plastic waste and interventions to tackle it has been recently published[10]. The authors' findings show that habits, norms, and situational factors were predictive of consumer plastic consumption and that political and psychological interventions were identified as being effective at curbing plastic consumption, albeit under-evaluated. However, the review was not conducted as a systematic review, nor was it structured within a behavioural framework or involve a meta-analysis. Considering the varied and multidisciplinary nature of the evidence on consumer behaviour relating to plastic waste (e.g. marketing[11], psychology[12,13], anthropology[14]), using behaviour change frameworks to synthesise this research within a systematic review and meta-analysis would increase our understanding of consumer behaviour with respect to plastic and the types of behavioural intervention that are likely to be effective at reducing plastic waste.

Theoretical framework

There are a number of models, theories and frameworks in the behavioural sciences that can be used to provide a behavioural analysis of a problem (i.e. to define problems in behavioural terms, understand why behaviours occur, and facilitate the design and evaluation of interventions to change behaviour). The Behaviour Change Wheel (BCW), shown in Figure 1, is an integrative framework, synthesising 19 such frameworks[15,16] and provides such a method for intervention development, intervention evaluation, and evidence synthesis.

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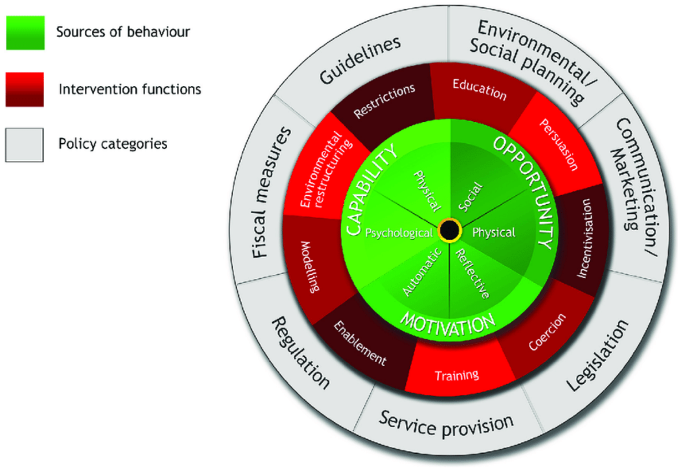
Figure 1. The Behaviour Change Wheel - a framework for intervention development, evaluation and evidence synthesis.



The BCW involves three key steps: 1. Specifying a target behaviour precisely; 2. Identifying influences on behaviour and, 3. Identifying effective interventions strategies (i.e. intervention functions, policy categories and component behaviour change techniques)

Clearly specifying a target behaviour is a key first step in a behavioural analysis of an issue[17]. It is difficult to understand and/or change a behaviour if it is vaguely specified. For example, a target behaviour such as 'reduce plastic waste' is not specific enough for a precise behavioural analysis or a targeted intervention. This is because there are a number of different behaviours people can engage in to reduce plastic waste (e.g., reducing, reusing, recycling). For clarity, it is important that the 'problem' of interest is precisely specified in measurable, behavioural terms (i.e. who needs to do what, to whom, where and when[16]). In order to precisely specify behaviour, the Action, Actor, Context, Target, Time (AACTT) framework[18] can be applied. Action refers to 'what' is being targeted for change (e.g. using a reusable coffee cup over a disposable coffee cup); Actor refers to the person(s) 'who' are part of the intervention (e.g. council authorities); Context refers to where the behaviour is performed (e.g. at the workplace); Target refers to 'whom' the behaviour effects (e.g. university students, employees, the general public); and Time refers to 'when' and for 'how long' the behaviour is performed (e.g. while grocery shopping).

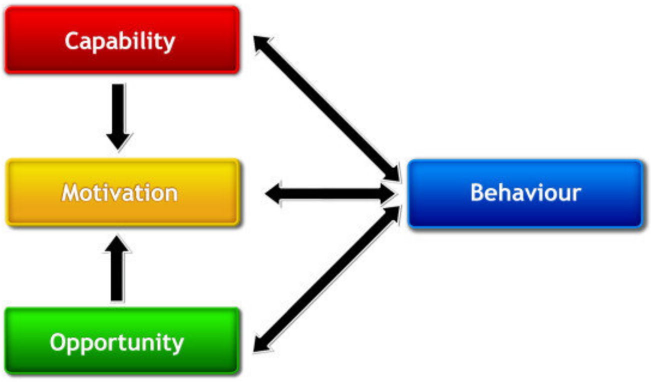
The Behaviour Change Wheel suggests that the second step in a behavioural analysis involves conducting a behavioural 'diagnosis'. Similar to the way that a physician diagnoses an illness to choose the most appropriate treatment, conducting a behavioural diagnosis involves identifying drivers of a behaviour that can be targeted by interventions designed to change behaviour. To guide the process of identifying influences on a behaviour, there are frameworks such as the COM-B (Capability-Opportunity-Motivation-Behaviour) model of behaviour[15,16] and associated Theoretical Domains Framework (TDF)[19]. Shown in Figure 2, COM-B posits that three pre-conditions must be met in order for behaviour to occur: having the Capability (i.e., physical and psychological abilities), Opportunity (the environment with which people interact including the physical environment of objects and events and sociocultural milieu) and Motivation (i.e., intentions, desires, evaluations, habits and instincts that energise and direct behaviour).

The Behaviour Change Wheel proposes that the final step involves identifying intervention types, policy categories to leverage the intervention, and component behaviour change techniques. The nine broad types of intervention identified by the BCW are; Education: increasing knowledge and understanding; Persuasion: getting people to change behaviour by generating 'cognitive dissonance' – an uncomfortable state of having contradictory beliefs, thoughts or values towards something; Incentivisation: changing the attractiveness of a behaviour by creating the expectation of reward; Coercion: changing the attractiveness of a behaviour by creating the expectation of punishment; Training: increasing psychological or physical skills; Restriction: constraining behaviour by setting boundaries; Environmental restructuring: altering the physical or social environment; Modelling: showing examples of the behaviour for people to imitate and Enablement: providing support to change behaviour in ways not covered by other intervention functions e.g. through encouragement, moral support.

The seven supporting policy categories include; Guidelines: development and dissemination of documents that make recommendations for desired behaviour; Environmental and social planning: changing the physical and social environment people inhabit; Communications and marketing: can include mass media campaigns and digital marketing campaigns; Legislation: Using laws and other similar instruments to set the restrictions on behaviour with penalties for breaching; Service provision: providing a service, material resource and aids; Regulation: Development and implementation of rules regarding behaviour that instruct the behaviour and possibly provide rewards and punishments for conforming and Fiscal measures: Use of taxation and tax relief. The aim here is to incentivise and disincentivise behaviours where one has authority to levy taxes.

In addition, each broad type of intervention may have one or more behaviour change technique(s) associated with it. For example, the intervention type Education could be achieved by techniques such as 'information about health consequences', 'feedback on behaviour' or 'self-monitoring of behaviour'. Ninety-three techniques have been identified defined within the Behaviour Change Techniques Taxonomy (BCTTv1)[20]. The BCW guide[16] offers ample guidance regarding the selection of BCTs that are best suited and most commonly used for each intervention type.

Figure 2. The COM-B model - a framework for understanding behaviour



COM-B posits that behaviour is the result of an interaction between three components: capability, opportunity, and motivation.

The frameworks introduced above have mostly been applied in intervention development but are increasingly being applied in systematic reviews and evidence syntheses (e.g. influences on diabetic retinopathy screening attendance[21] and influences on chlamydia testing in general practice for young people and primary care practitioners[22]) to maximise learning and consolidate findings from diverse studies drawing on varied research methodologies. Systematic reviews using the BCTTv1 and BCW to identify active ingredients of interventions include a review of BCTs in built environment interventions to increase use of green space[23] and a review examining the content of interventions supporting parents of 3- to 8-year olds to reduce provision of unhealthy food[24].

The present review

We aim to use the behavioural frameworks introduced above to synthesise evidence concerning consumer behaviour related to plastic waste. We will do this by identifying behaviours, behavioural influences, and the most effective interventions to reduce plastic waste. The focus will be on consumers as they represent a central part of the plastics system in the sense that they buy and use plastic, and are responsible for initiating plastic's pathway after use (e.g., putting it in a bin intended for landfill, a recycling bin, or cleaning for reuse).

Objectives

To this end, the objectives of the present review are to:

1. Identify the specific (consumer) behaviour(s) that have been investigated as potentially influencing plastic waste (i.e. who / what / where / when / with whom).
2. Identify factors that influence people's behaviour with respect to plastic waste and categorise these in terms of capability, opportunity, and motivation (i.e., components of the COM-B model).
3. Identify studies evaluating behaviour change interventions to reduce plastic waste and;
   a. Specify intervention content using Behaviour Change Wheel intervention types, Behaviour Change Wheel policy categories and Behaviour Change Techniques,
   b. Evaluate the impact of the intervention on behaviour
   c. Evaluate which intervention components are most effective (in the sense of being positively associated with effect sizes).

Method

Search strategy

We will use two search strategies to identify papers. In February 2020, we conducted a search of three electronic databases (namely, PsychINFO, GreenFILE, and Scopus). The search was limited to English language and peer reviewed journal articles and had to include one or more of the search terms from each filter in its abstract. Once we have completed identifying a preliminary set of papers from the electronic database search, we will supplement this list by searching for other potentially relevant studies using a snowball strategy[25] of searching backward and forward citations.

Keywords for the electronic database search were chosen to reflect three filters: (i) plastic; (ii) behaviour and; (iii) behavioural influences and/or behaviour change intervention. Table 1 summarises the keywords used.

Table 1. Database search terms

Plastic filter	Behaviour filter	Influence/intervention filter
plastic*	behavio?r*	behavio?r*change
microplastic*	practice*	impact*
poly?coated	recycl*	predictor*
	reus*	influence*
	consum*	factor*
	reduc*	barrier*
	refill*	enabler*
	return*	facilitator*
	repurpos*	intervention
	upcycl*	strateg*
		polic*
		management
		implement*
		campaign

Study eligibility criteria

Inclusion/exclusion criteria;

1. The study must explore consumer behaviour associated with the purchase, use and disposal of plastic objects. Our working definition of behaviour is "*Anything a person does in response to internal or external events. Actions may be overt (motor or verbal) and directly measurable or, covert (activities not viewable but involving voluntary muscles) and indirectly measurable; behaviours are physical events that occur in the body and are controlled by the brain*"[26]

2. The study must measure potential influences on a behaviour(s) related to plastic waste (e.g., attitudes, beliefs, aspects of the environmental context)

AND/OR

3. Evaluate an intervention designed to change behaviour related to plastic waste;

Additional criteria;

To be included in the meta-analysis of the effect of interventions in changing behaviour and reducing plastic waste the studies must;

1. Expose participants to an intervention designed to promote behaviour that reduces plastic waste (or reduce a behaviour that increases plastic waste),
2. Measure one or more behaviours or outcomes related to reducing plastic waste,
3. Contain sufficient information in order to extract or compute an effect size representing the effect of the intervention on behaviour and / or outcomes. Studies will be excluded if the effects of the intervention are not reported in a way that allows estimation of effect sizes and this information cannot be obtained via correspondence with the authors.

Screening procedures

Electronic database search

The screening of potential articles is being completed by three reviewers (ALA, CL, HMB) in a phased approach; title and abstract screening followed by a screening of full texts, according to the predefined study inclusion/exclusion criteria.

Two researchers (ALA and CL) independently screened 10% of title and abstracts (k = 408) and compared the results to assess reliability of screening assessments. 91% agreement was achieved. Discrepancies were discussed until 100% agreement was reached. As reliability was high, ALA independently continued with title and abstract screening, completing in March 2020.

Full-text screening was completed in May 2020. 10% of full text articles (k = 15) were double screened by ALA and HMB and results compared to assess reliability of screening assessments. 87% agreement was achieved. Discrepancies were discussed until 100% agreement was reached. As reliability was high, ALA independently completed full text screening.

'Snowball' search

Once we have our final set of papers from the database search, one researcher (ALA) will backwards search the reference lists and forward search other studies that have referenced the included papers to identify other potentially relevant papers. Full texts of these potentially relevant papers will then be screened and assessed according to study inclusion/exclusion criteria. A second reviewer (HMB) will review the selected studies. A study will only be included if both researchers agree on its eligibility.

Data extraction

Data extraction forms will be developed and piloted for this review, in accordance with Cochrane guidance[27]. Data extraction will be completed by the primary researcher (ALA) and 10% of data extracted will be also be reviewed by a second researcher (HMB). Data extracted will include:

1. Study characteristics (i.e., authors, journal, date, study context, study design, population)
2. Written description of the behaviour(s) investigated
3. Results reporting influences on behaviour (e.g. direct quotes, author summaries)

AND/OR

4. Description of the intervention (e.g. intervention summary reported in the paper)
5. Information to compute effect size for meta-analysis (e.g. effect size, standard error, confidence intervals, references ranges, ranges, IQR, significance test, p-value)

Data analysis

Descriptive statistics will be used to summarise study characteristics and results will be presented in tables.

To address our first research objective – i.e. identify the specific (consumer) behaviour(s) that have been investigated as potentially influencing plastic waste – behaviours will be summarised descriptively in terms of Action, Actor, Context, Target, and Time, and results presented in tables.

To address our second research objective – i.e. to identify factors that influence people's behaviour with respect to plastic waste and categorise these in terms of capability, opportunity, and motivation – influences on behaviour will be analysed in line with Braun and Clarke's guidance on qualitative analysis[28]. This method will include two phases: Phase 1 will involve an inductive thematic analysis to generate content themes of behavioural influence. Phase 2 will involve mapping themes generated onto COM-B categories to summarise influences in terms of capability, opportunity and motivation.

To address our third research objective – i.e. identify studies evaluating behaviour change interventions to reduce plastic waste – we will descriptively summarise (i) the range of Behaviour Change Wheel intervention types, (ii) the range of Behaviour Change Wheel policy categories and (iii) the average and most and least frequently identified Behaviour Change Techniques per intervention. We will also use meta-analysis to compute a sample-weighted average effect of the interventions on outcomes. This will tell us whether behavioural interventions are, on average, an effective way to reduce plastic waste and, if so, how effective they are. Where there is sufficient evidence (i.e., more than 3 studies representing a particular type of intervention) we will compute sample-weighted average effect sizes for different types of intervention (e.g. those targeting capability, those targeting opportunity, those employing specific behaviour change techniques) and then compare effect sizes to identify which features are associated with intervention effectiveness.

Conclusions

Human behaviour rests at the core of the plastic waste issue - overconsumption and inappropriate waste management. As a result, technological breakthroughs alone will not suffice in curbing generation of plastic waste - we also need perspectives focussed on changing behaviour. However, there are limits to achieving the desired changes in behaviour without a thorough understanding of how and why it occurs. Consequently, there is great value in a systematic and principled approach to understanding the role of behaviour (and changing behaviour) in reducing plastic waste. We hope that this review prompts the scientific community to consider the central role of behaviour in generating plastic waste. In addition, we hope our findings inform future behaviour change interventions and identify areas for further research aimed at understanding and reducing plastic waste.

Conflicts of interest

There are no conflicts to declare.

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Towards a new Regional Circular Economy for Plastics - Progress in South West England

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We overview the work of **ExeMPLaR** (**Exe**ter **M**ultidisciplinary **Pla**stics **R**esearch Hub: (https://exemplarnet.org.uk/) focussing on the plastic system of the South West England region (SW), defined for this study as three counties (Cornwall, Devon and Somerset. The project was designed to assess how regional actors and stakeholders might develop future circular economy plastics systems from the bottom up and find evidence for effective future change that could be replicated and scaled elsewhere, potentially informing future national policy. Moreover, we were keen to apply University of Exeter's world leading research in marine science and ecotoxicology to develop the scientific evidence and awareness of the potential ecological and human health impacts of plastics entering the environment. We also sought to apply social science expertise in relation to policy and behaviour change to help generate understandings of the role of people, organisations and policy-makers in mainstreaming a circular plastics economy. In doing so, our intention was to inform policy makers, polymer chemists, manufacturers, recyclers and the wider population on the principle of '*safer by design*'. Here, we present a range of findings to date from **ExeMPLaR**, to illustrate the scale, complexity and opportunity to move towards future circular systems. **Section 1** presents some headline data to illustrate the variety, stocks and flows of plastics in the regional system, some of its impacts (beach litter, impacts on wildlife) and the sizable and very active number of initiatives on plastics, each with their own goals, world views and values (e.g. Plastic Free Towns initiative). We also comment on the challenges of data availability, and lack of research on impacts and their outcomes. **Section 2** provides a thumbnail of a sample of interventions, demonstrators and case studies initiated, supported and/or promoted by **ExeMPLaR** and its partners to illustrate some of the component parts, enablers and opportunities of a future circular system. In **ExeMPlaR** we have begun to bring together a network of transformative change towards a circular economy for plastics, in the SW region. Crucial for the network's success is to bring together key competencies (and associated sectors) including: academic knowledge, communities on the ground, relevant businesses and supply chains, governance (*e.g.* local and regional government), environmental organisations, and media - to spread success stories and learning-by-doing. These actors are the key 'nodes of influence' of the network who come together with a plurality of understandings around a shared 'A-story' - to co-produce a regional circular economy for plastics. They work together to identify shared values that underpin their collective actions, and generate ideas for transformative change. These create the focus for Hubs of activity, and specific pilot initiatives. In 18 months, we have only just begun to bring together the network of change, but it is already an important legacy of the project. The key challenge for the work we have conducted to date is to maintain momentum and commitment and validate, scale and replicate successful interventions underpinned by scientific evidence. Current plastics' infrastructure, policies and behaviours has evolved over several decades and turning this around to circular systems will take time. Advances in polymer chemistry, biotechnology, waste sorting, segregation and reclaim and chemical recycling will continually alter the resource-from-waste landscape and future economic, social and environmental opportunities. It goes without saying that a strong, committed regional and local leadership is required, with a clear vision and an ambitious and feasible Road Map guided by circular economy principles, regional stakeholders and national imperatives.

Introduction

A circular economy approach to plastics simultaneously addresses the accumulation, impact and costs of plastic waste and pollution in the environment, whilst maintaining applications for multiple high value purposes. This includes uses in medicine, engineering, construction and extending food product life, thus making a significant contribution to the global and UK economy and the livelihoods of millions of people. Increased value can be achieved by maintaining the integrity of a product or material at a higher level (technical and economic durability), using products for longer (repeat use), cascading their use in adjacent value chains, and designing pure, high quality feedstocks at the outset so avoiding contamination and toxicity. A key challenge for a

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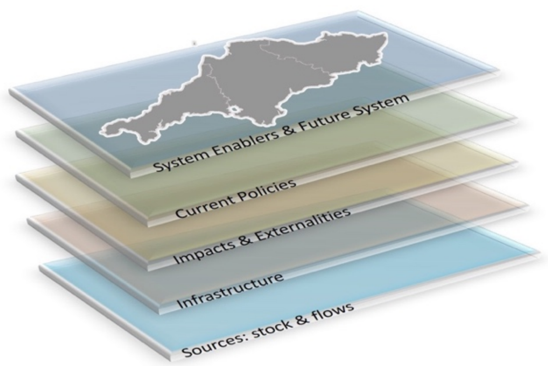
plastics circular economy is the proliferation of highly functional but low value end of life plastic products. Their usefulness and the low price of oil are contributory factors to forecasted rates of growth, with plastics production estimated to double within the next 20 years. Fossil fuel derived plastics are by themselves at odds with a move towards renewable resources. However, replacing current plastics with bio-based materials will take land out of food production [1]. Therefore, to create a future plastic circular economy will require reducing unnecessary consumption and future innovations that avoid regrettable substitutions.

Such an approach is inherently a complex system challenge involving many actors, practices, and variables that have evolved over decades [2]. The mismanagement and leakage of highly durable plastic into the environment is one example of a system failure at scale that has attracted global concern and action. In the UK, there is concerted action at national scale, such as the ban on the manufacture of products containing microbeads, the single-use plastic carrier bag charge and, more recently, Pact (http://www.wrap.org.uk/content/the-uk-plastics-pact) to address the problems created by mass production and consumption of single-use plastics. HM Government's 25-year Environment Plan aims to be "Working to a target of eliminating avoidable plastic waste by end of 2042". New policy initiatives such as a Deposit Return Scheme (DRS) and Extended Producer Responsibility (EPR) are proposed in the forthcoming Environment Act. These are economic instruments designed to incentivise producer and consumer behaviour change. A future output from ExeMPLaR is to propose how future national policy and regulatory changes can be configured to support circular economy benefits at regional scale [3].

Outside of these and other national initiatives, the **ExeMPLaR** (**Ex**eter **M**ultidisciplinary **Pla**stics **R**esearch Hub; https://exemplarnet.org.uk/) project was designed to assess how regional actors and stakeholders might develop future circular economy plastics systems from the bottom up and find evidence for effective future change that could be replicated and scaled elsewhere, potentially informing future national policy. Moreover, we were keen to apply University of Exeter's world leading research in marine science and ecotoxicology to develop the scientific evidence and awareness of the potential ecological and human health impacts of plastics entering the environment. We also sought to apply social science expertise in relation to policy and behaviour change to help generate understandings of the role of people, organisations and policy-makers in mainstreaming a circular plastics economy. In doing so, we sought to inform policy makers, polymer chemists, manufacturers, recyclers and the wider population on the principle of '*safer by design*'.

ExeMPlaR focuses on the plastic system of the South West England region (SW), defined for this study as three counties (Cornwall, Devon and Somerset; **Fig 1**). These counties comprise a resident population of over 1.9 million people, large urban centres (Bath and Taunton, Plymouth and Exeter, St Austell and Falmouth) with high levels (in national terms) of tourism, agriculture, and fishing. Figure 1 summarises the five interconnected layers of the **ExeMPLaR** project: 1. understand, quantify and map the current system and quantify stocks and flows of plastics from all sources. 2. map and link the multiple infrastructure and pathways for the collection, segregation and treatment of plastics at the end of their first use phase. 3. identify and assess impacts of 'plastics', in multiple life cycles on ecosystems and human health. 4. link layers 1-3 to the policy and regulatory landscape to highlight relationships that influence investments, product design and labelling, stakeholder behaviours (including voluntary behaviours) and costs. 5. develop a common vision for a future system, find out what is working well currently to replicate and scale, and work with regional stakeholders on networks for change and innovative high value circular solutions within a systems framework. Here, we present a range of findings to date from **ExeMPLaR**, to illustrate the scale, complexity and opportunity to move towards future circular systems. **Section 1** presents some headline data to illustrate the variety, stocks and flows of plastics in the regional system, some of its impacts (beach litter, impacts on wildlife) and the sizable and very active number of initiatives on plastics, each with their own goals, world views and values (e.g. Plastic Free Towns initiative). We also comment on the challenges of data availability, and lack of research on impacts and their outcomes. **Section 2** provides a thumbnail of a sample of interventions, demonstrators and case studies initiated, supported and/or promoted by **ExeMPLaR** and its partners to illustrate some of the component parts, enablers and opportunities of a future circular system. Two other papers describe in more detail a household plastic stock-flow model and evidence of motivation, commitment and action around plastics by formal and informal regional community networks [4,5].

Figure 1. Five layers of ExeMPlaR project.



Section 1: The current plastic system

A key first step in an evidence-based approach to the assessment and design of future circular economy systems is to quantify stocks and flows, points of leakage and opportunities for the mitigation potential of different practical interventions and economic value creation. The challenges of building national or regional resource stock-flow models is well known. In our case, data on plastic inputs and outputs, stocks and flows across sectors and activities are highly fragmented and contain many uncertainties. Available data on the proportion of different plastic types in waste streams are often limited. The best data on waste flows derive from statutory household waste collection reporting requirements via local authorities – often with discrepancies and limited resolution in terms of material composition. Data on commercial waste flows or treatment pathways are often confidential or, where available, out of date. The project therefore has spent time piecing together available data sets, created models or made best estimates from first principles.

Regional stocks and flows: To illustrate the volume of plastics in the regional economy and the scale of any system redesign, local authority data on kerb-side collection, recycling centres and street collection indicate that these generate around 125,000 tonnes of plastic per annum of which 41,000 tonnes is incinerated, 55,000 tonnes landfilled and 26,000 recycled, either in the UK, or sent for export; the balance is unidentified or unaccounted for. Whilst there is rightly a high level of focus in national policy on single-use plastic packaging, household plastic consumption includes a far greater range of products than is generally reported or appreciated. In a separate contributed paper, a novel **ExeMPLaR** household plastic footprint calculator method is described [5]. This quantifies the total average stock of plastic in households nationally and the average flows of all plastics from households in the SW including clothing, footwear, building products, vehicles, white goods, and packaging. The total stock of plastic in SW households is around 1M tonnes at an average of around 0.5 tonne per person, or just over 1 tonne per household. More than half the stock is in building components. Plastic outflows per person is approximately 70kg per annum – including kerb-side disposal. Bioplastics, which attract widespread media and public attention, are not recorded separately but material recovery facility operators indicate this a very small fraction of total plastic waste currently.

Beyond domestic consumption and disposal, key economic sectors to the regional economy (fishing, agriculture and tourism) represent under-researched sources of plastic stocks and flows. Regional data show plastic waste in the SW increases by around 40% in the peak tourist season. In the case of fishing and agriculture, whilst the amounts are smaller than for households, they are nonetheless significant and give rise to specific impacts of concern.

Fishing: Abandoned, lost or discarded fishing gear has been identified as a major source of plastics in marine environments. An estimated 46% of plastic in the 'Great Pacific Garbage Patch' [6]. and 27% of beach litter results from the fishing industry [7]. A typical net on a UK trawling vessel contains around 0.5 tonne of plastic - usually nylon - and another 0.5 tonne of other materials including metals. The high cost of disposal or repair relative to the cost of new gear, compounded by a historic lack of collection and recovery systems has, until recently, reduced incentives to recycle or reprocess fishing plastic (see **section 2**). Data published by the *Marine Management Organisation* combined with specifications of fishing gear materials show a wide range of estimates of plastic waste of up to 6000 tonnes per year, comprising Devon ports (1478-3022 tonnes per year), followed by Cornwall (650-2680 tonnes per year) and Somerset (<1 tonne per year). These values are an underestimation of the plastic waste produced, as they assume one net replacement per year and exclude non-net plastic (e.g. buoys, rope, containers and other consumables).

Agriculture and soil: Plastic in agriculture and soil has three major sources: 1) in the production process via silage wrapping, field scale 'mulching' to extend the growing season by protecting early season crops, and packaging for fertilisers and pesticides. 2) via sewage sludge spreading that contains microplastics from water treatment and/or anaerobic digestion processes. 3) soil recovered from building and related works that are then screened and often resold with hidden plastic. Airborne sources (e.g. tyre particles from roads) add a further unknown quantity. Data on the consumption, use and disposal or recycling of farm-scale practises are scant and commercially sensitive. Data from the Farming and Wildlife Advisory Group (FWAG) combined with estimates of acreage of specific early season crops allowed us to estimate between 3000-5000 tonnes of mulch plastic for three early season crops (barley, wheat, and potatoes). Plastic mulches and fleeces readily fragment and accumulate in soil where they adsorb agrochemicals [8]. Data on the magnitude of sewage sludge spreading, and the associated concentrations of microplastics, are not available. Recent research elsewhere, however, has shown typical levels of 2,000-4,000 microplastics particles/g dry weight of sludge [9]. The impacts of plastic accumulating in the soil are not well understood. Microplastics interact with soil, reducing their ability to provide important ecosystem services. Composts made from household waste can legally contain up to 5% plastic although this is currently under review.

Leakage into marine environments Data collection during organised beach cleans is an established method of investigating the status of anthropogenic litter, for both the beaches themselves, and as an indicator for the wider marine environment [10]. The use of volunteers as *citizen scientists* to record litter is a cost-effective method of generating large long-term datasets, which enable patterns and trends to be identified over broad spatial and temporal scales.

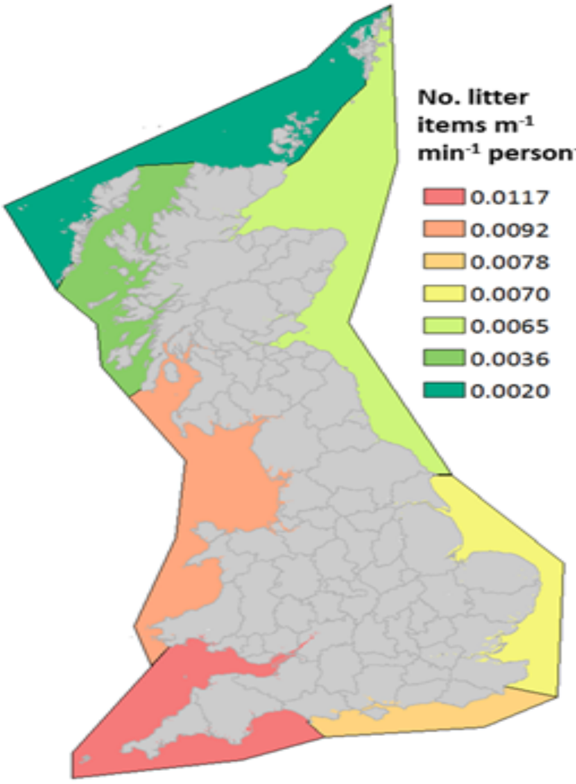


Figure 2. *Regional mean number of litter items (m^{-1} min^{-1} $person^{-1}$) collected during MCS beach cleans from 2005 to 2014. Adapted from* [11].

Three of the largest beach clean operators in the UK (*Keep Britain Tidy*, *Marine Conservation Society; MCS,* and *Surfers Against Sewage; SAS*) manage approximately 180,000 volunteers across the UK and have a very strong presence of activity in the SW. The **ExeMPLaR** team has been working closely with these, and other, organisations to study and enhance this citizen science activity to help monitor trends of overall abundance of marine litter and its composition, so informing and encouraging mitigation efforts. Work over the last five years by the three organisations detailed above has resulted in an estimated average of 17.5, 4.3 and 4.2 tonnes of marine litter per annum being removed from beaches in Cornwall, Devon and Somerset, respectively. A detailed analysis of the dataset generated by the *Marine Conservation Society* suggests that approximately 70% of beach litter is made from plastic [11,12]. Regionally, the SW experiences the highest mean density of overall litter (Fig 2), as well as specific items such as plastic food and drink packaging, and fishing gear when compared to other regions in the UK. Although the most common identifiable source of items by frequency is public littering (36%; [11]) due to logistical challenges, items are not always weighed and marine borne litter, such as abandoned, lost and or otherwise discarded fishing gear, makes up a much greater proportion of the litter by mass.

Infrastructure: The majority of household plastic waste in Cornwall and Devon is incinerated whereas Somerset has commissioned a new resource recovery centre which will reduce its current high waste-to-landfill statistics. Waste-to-energy plants are major investments that create long-term contractual and technical lock-in and a potential barrier to future circular systems. Regionally there is a network of hundreds of registered and licenced waste carriers - many of them small. Estimating the full waste management cost of the current system is hindered by commercial sensitivity. Estimates of revenues from local authority sale of higher value plastics have been obtained. The unaccounted costs of plastics on ecological or human health impacts are equally complex and lack reliable evidence or precision. One study estimated the negative economic impact of marine plastic at between US$3,300-33,000 per tonne [13]. Substituting plastic for other materials, such as glass, needs careful assessment of impacts across the whole life cycle(s). For example, **ExeMPLaR** has shown that the substitution of PET with glass as the material for some bottles under the current waste infrastructure and management practices could lead to significant increases in environmental impacts [14].

Eco-toxicology impact: Concerns about the impact of fuel-based plastics in the environment include their very slow degradation into smaller particles that become more toxic as they can pass more easily through biological barriers. Also, hazardous chemical additives used in their manufacture (*e.g.* plasticizers) will be released and chemical micropollutants that adsorb on microplastics (ingested, or inhaled or touched) will lead to exposure via a trojan horse mechanism. Biodegradable bioplastics (compostable or not), cannot automatically be assumed to be safe. A comprehensive, systematic and scientifically rigorous ecotoxicological assessment of 'plastics' involves 2 key stages. Firstly, data on all sources, manufacturing processes, chemical additives and recycling/biodegradation knowledge is collated. Secondly, a series of controlled laboratory ecotoxicity tests are undertaken following international accepted protocols and experimental set ups that account for the complex nature and fate of the plastics in the environment. As part of **ExeMPLaR** demonstration projects reported in **section 2,** we focussed on a shortlist of plastics.

Human health impact: Many chemicals used in plastic production (plastic additives) are hazardous to humans [15], who may be exposed occupationally [16] through subsequent use of the product or due to transfer into food products from plastic packaging [17]. Recent evidence has also shown that a number of recycling processes can lead to migration, contamination and accumulation of potentially hazardous substances in secondary materials. While for some countries, appropriate regulation may limit their secondary use and value, in others this impact may remain unchecked and contaminated plastics can end up in circulation [18]. In order to understand the potential for human health impact outcomes of recycled plastics, we are conducting an overview of existing high-level research that examines the impact of phthalates (a plasticising chemical additive) on a range of human health outcomes. Phthalates have been chosen for focus as they are likely to accumulate through recycling processes, and because plastics form the predominant source of high-molecular weight phthalates in the body [19]. **ExeMPlaR** has undertaken an overview of published reviews to establish the current knowledge on health outcomes of exposure to plastics. Across 42 reviews, health effects ranged widely, including impacts on the reproductive and respiratory systems (e.g. sperm abnormalities; asthma symptoms), congenital defects (e.g. genital abnormalities); behavioural disorders and cognitive development. Conclusions from this evidence base are difficult to draw, due to the different exposure pathways by which plastics may enter and impact the body, leading to a range of study methodologies and conflicting results. For some outcomes there exist mainly non-human studies, which do not simulate the real-world, additive effects of chemical exposures.

Environmental Impacts**:** A key public concern around plastic is the negative impacts on the environment, wildlife and the contamination of our marine food supply.

The UoE team has found that microplastics are present in wild-caught mackerel and is ubiquitous in seals and dolphins in the SW [20]. This work has been extended within **ExeMPLaR** to studies of four species of shark (dogfish) that are frequently consumed by humans showing that microplastics were ingested by all individuals [21]. Entanglement in marine debris has been internationally recognised as a potential threat to marine species (Fig 3). In Cornwall, [22] estimated that the observed annual mean entanglement rates of local seals varied from 3.6% to 5%. The majority of identified entangling material was fisheries-related and in addition to welfare concerns, data suggested an increased mortality rate in affected seals. For large marine vertebrates, such as marine mammals, the population-level effects of mortality from entanglement in and ingestion of plastic pollution are not well understood, but are key indicators of impacts on the wider marine environment.

Figure 3. Entangled grey seal (Photo: Sue Sayer) WRAP.

Section 2: Creating future circular economy: Interventions, tipping points and networks of change

In the space limitations we have selected the following examples of interventions, demonstration projects and lessons learnt to date to both positive directions of change and the need for continued systemic approaches to the formation of circular plastic systems. In all cases analysis is on-going.

Creating regional loops: The SW generates a large amount of plastics waste, some of which fetch prices of around £200/tonne (clear PET) and £400/tonne (HDPE). Baseline data have shown that the plastics collected within the region for recycling is 'exported' to reprocessors in the North of England or abroad. A significant percentage of the region's higher value plastics are currently not recycled or re-used. There are large amounts of plastics leaking into the regional environment through various pathways causing unknown costs.

During **ExeMPLaR**, we have identified, collaborated with, and been approached by many innovative SMEs operating within a circular economy framework - but not necessarily using that term. Some examples include: Flexi-hex is a growing business who produce a range of products from reclaimed single use plastics (https://www.flexi-hex.com/); Odyssey Innovation (https://www.odysseyinnovation.com) collect plastic waste from marine environments in the SW which are used to make the world's first recycled plastic kayaks which are retailed and also promoted as part of an international Paddle for Plastics campaign; Fishy Filaments (https://fishyfilaments.com/) who recycle nylon fishing nets collected in the region into engineering grade materials for 3D printing and new nets. Currently the nets have to be sent to Denmark for reprocessing due to lack of UK infrastructure; Circular & Co (https://circularandco.com/), works with many multinationals to find innovative solutions to end of life plastic wastes. Sales of rCup made from recycled polypropylene (PP) exceed half a million but manufactured in China due to availability of low-cost tooling and access to food grade PP. Working with **ExeMPlaR** and other partners, the company is now designing and testing the local manufacture of a new food grade reusable drinking from recycled PET collected via dedicated on-the-go collection systems. Evidence has shown that regionally co-ordinated actions with appropriate financial support for collection systems for fishing nets could significantly reduce the loss and dumping of fishing plastics with environmental benefits and scope for scaling up recycling and re-use opportunities. We have identified many other sectoral opportunities currently not being exploited that have the potential to create virtuous circular value creation opportunities.

Future plastics, Safer by design: The re-use of recycled plastic or use of new biomaterials needs to avoid contaminating products with potentially hazardous or toxic substances, which can impact human health or ecological systems and destroy the economic value of the recycled material and undermine public confidence in ‘recycling’ or ‘circular economy’. In considering ecological impacts, we have followed a ‘safe-by-design’ philosophy, conducting ecotoxicity tests to determine the sensitivity of aquatic organisms at the base of the food chain, comparing the effects of petrochemical-based plastics with new, bio-based, sustainable polymers, recycled materials and packaging alternatives. Traditional testing approaches have been modified to consider not only the microplastics, but also the chemicals and pollutants that associate with them in freshwater and the marine environment. This is delivering new data to inform and guide sustainable choices for the future use of plastics and their alternatives. Bioplastics are one of the potential solutions but need to be designed to ensure they can cascade to the biosphere safely. Even then a high input in a lentic (low flow rate) aquatic system could disrupt the ecosystem dynamics and lead to unintended environmental impacts.

A regional bioeconomy: The importance of farming, fishing and forestry in the SW economy creates opportunity to utilise regional resources to create alternatives to synthetic plastics, support place-based manufacturing and jobs. An example of the potential is local entrepreneurs working with the *Marine Biology Association* have applied for planning permission to set-up a seaweed farm in Devon to grow and harvest two native species. **ExeMPlaR** is working with *Materiom* (https://materiom.org) to test three regionally abundant plant and animal by-product materials as potential alternatives or substitutes for fossil fuel derived or questionable biodegradable plastics (see below, citizen confusion). Initial hackathons attracted local entrepreneurs and a follow up ‘design sprint’ and product prototyping has been rescheduled pending the Cov-19 lockdown. For now, the preliminary results have shown that our initial sample of fish-based, pork-based and algae-based bioplastics are not acutely ecotoxic to marine and freshwater zooplankton.

Complex systems, targets and performance frameworks: A regional plastic economy is an example of a complex adaptive system. Working with stakeholders we have used soft system mapping techniques to draw out the complex interdependencies (known as causal loops) between many different variables (sources, pathways, fate etc) to build a shared view at what is driving the behaviour of the system towards desired/undesired goals and end states. This enables us to work with stakeholders to maintain a picture of the whole system and begin to build a systems dynamics model to quantify outcome from future scenarios (see below Networks for Change). Alongside this, there is a need for a comprehensive but simple dash-board of performance indicators to show what activities, policies, enabling mechanisms and actions are needed over the next 15-20 years across multiple institutions and actors to create future circular economy. We are currently building such an initial framework with stakeholders.

Future Citizen Science: Refining methodologies to create citizen science data best suited to inform policy is the subject of two small follow-up projects funded by UKRI and Research England, respectively. An unexpected highlight of this work is our interaction

Figure 4. The Tidal Revival App

with Cornwall-based *Evidence Plastic CIC* who have developed the mobile phone application *Tidal Revival*, currently live on the App Store and Google Play and now with several thousand users (Figure 4 above).

The App rewards people for every piece of plastic litter picked up from beaches and water courses**,** it logs the categories of plastic recovered together with the location of the recovery and a photo of the plastic itself. Points rewards are then exchangeable for discount vouchers from sponsoring local businesses. The app has strong potential to incentivise positive change on several levels. It can facilitate environmental clean-up at unprecedented levels, enable data gathering on a common platform at massive scales and, when appropriate feedback mechanisms are built in, create communities of change in users and sponsoring businesses. The **ExeMPLaR** team are at early stages of brokering relationships with NGOs to partner with *Tidal Revival*.

A hub of environmentalism: The SW region has a very strong connection with environmental networks. Indeed, the **ExeMPlaR** team found that there are more community level initiatives addressing plastic within the SW than in any other UK region. Cornwall is home to the nationally active NGO, *Surfers Against Sewage* (SAS) who have led a widespread movement of Plastic Free Communities (https://www.sas.org.uk/plastic-free-communities/). As of May 2020, there are 681 registered Plastic Free Communities and a growing number of approved communities that have gone through an accreditation process. Working with SAS and their engaged members, we undertook a mixed method approach to evaluate who is getting involved in the campaign, why they are getting involved, and what impact it is having on them. An online survey, distributed by SAS and followed up by semi-structured interviews with community leads, formed the basis of the research. The findings broadly support previous research into the demographics of environmental movements [23,24] Participants typically have underlying eco-centric attitudes and have been galvanised by increased media focus and visibility of plastic pollution in the environment.

Future Circular Economy communities: More than 300 regional initiatives were identified, which fell into three categories: [a] addressing plastic pollution in the local environment, [b] systemic transitions around reducing, reusing, repurposing, repairing, and sharing (*e.g.* repair cafes, sharing libraries), [c] new and emerging businesses with the potential for positive economic impacts within communities. The initiatives we identified are widely dispersed throughout the region, with the majority of activity taking place in rural and coastal towns. These areas are frequently at the forefront of the negative impacts of economic downturns and wider restructuring. Our research has shown that increased interest in community initiatives and place-based organising is making a contribution to a regional circular economy for plastic through a range of social and economic practices that slow the loop, including keeping household items in use for longer through repair initiatives and reuse facilities, and reducing the need to buy new products by facilitating shared access to product services and sharing libraries. Furthermore, **ExeMPLaR** research has revealed that involvement with initiatives such as Plastic Free Communities has positive social impacts for individuals, businesses and their communities. Promoting the positive effects of community participation, such as social cohesion and a sense of belonging, may therefore prove more effective in broadening the campaign's reach than solely relying on a pro-environmental message.

Citizen action, citizen confusion: Despite the high levels of engagement and support for taking action around 'plastics', our workshops and knowledge exchange activities revealed widespread confusion, lack of trust and wish for better information and communication about products and disposal methods. Numerous examples of businesses and citizens switching to 'biodegradable' or 'compostable', often at higher cost, has been met with disillusionment at the lack of collection and sorting facilities and the swirl of rumours and stories that they do not biodegrade and in fact may be worse for the environment than fossil fuel plastics. Many active citizens are themselves scientists, knowledgeable and/or part of informed scientific based networks and monitor and test claims about biodegradation. One attendee bought a latex balloon stored in sea water, and asked how this could be labelled biodegradable when there was no evidence of any decomposition after 3 years. Whilst people want change, there is clearly a risk of doing the 'wrong things perfectly right'.

Networks for changes and Tipping points: The theory of complex systems and tipping points shows that sometimes deliberate interventions triggering tipping points at small scales can encourage tipping points at larger scales, and so on [25]. Tipping points are where a small change (or 'perturbation') has big consequences - changing the state or fate of a system. We call this an 'upward-scaling tipping cascade' and we see the potential to trigger such cascades towards a circular economy for plastics. As shown above there is a great diversity of bottom-up initiatives that are self-organising to create change. These initiatives can be disparate and disconnected and this can impair their ability to create change. However, if they network together supported by the right social actors they can be powerful collective agents of change. For the plastics problem this needs *transformative* change in that the whole plastics system and economy needs to be transformed.

Conclusions

In **ExeMPlaR** we have begun to bring together a network of transformative change towards a circular economy for plastics, in the SW region. Crucial for the network's success is to bring together key competencies (and associated sectors) including: academic knowledge, communities on the ground, relevant businesses and supply chains, governance (*e.g.* local and regional government), environmental organisations, and media - to spread success stories and learning-by-doing. These actors are the key 'nodes of influence' of the network who come together with a plurality of understandings around a shared 'A-story' - to co-produce a regional circular economy for plastics. They work together to identify shared values that underpin their collective actions, and generate ideas for transformative change. These create the focus for Hubs of activity, and specific pilot initiatives. In 18 months, we have only just begun to bring together the network of change, but it is already an important legacy of the project.

The key challenge for the work we have conducted to date is to maintain momentum and commitment and validate, scale and replicate successful interventions underpinned by scientific evidence. Current plastics' infrastructure, policies and behaviours has evolved over several decades and turning this around to circular systems will take time. Advances in polymer chemistry, biotechnology, waste sorting, segregation and reclaim and chemical recycling will continually alter the resource-from-waste landscape and future economic, social and environmental opportunities. It goes without saying that a strong, committed regional and local leadership is required, with a clear vision and an ambitious and feasible Road Map guided by circular economy principles.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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Influences on single-use and reusable cup use at University College London: a mixed methods study

Susan Michie,[a] Ayse Lisa Allison, [b] Fabiana Lorencatto [c] and Mark Miodownik [d]

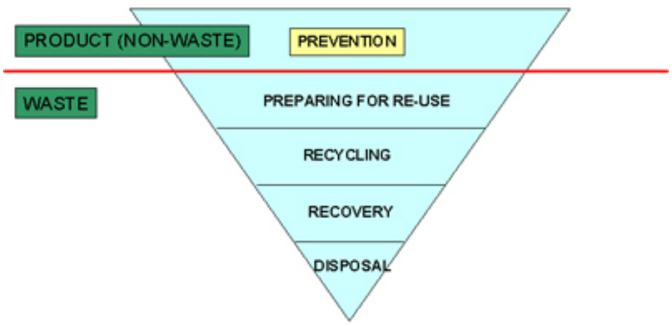
Per year, an estimated 2.5-5 billion single-use coffee cups are disposed in the UK, most of which consist of a plastic lining. Due to the difficulty of recycling poly-coated material, most of these cups end up as litter or in landfill contributing to environmental degradation. UCL's Plastic Waste Innovation Hub are leading formative research to inform development of an intervention to eradicate single-use cups across UCL campus. This study aims to identify barriers and enablers to use of single-use use and reusable cups amogst UCL students and staff. This will be achieved via an online survey and follow-up interviews. The survey and interview materials are based on the Theoretical Domains Framework, a framework of 14 theoretical domains depicting the various individual, socio-cultural and environmental influences on a behaviour and the COM-B model of behaviour, which identifies the key factors required for a behaviour to occur: Capability (psychological and physical), Opportunity (physical and social), and Motivation (reflective and automatic). Findings from the survey and interviews will form a basis for selecting potential intervention strategies using the Behaviour Change Wheel approach. Basing the design of the intervention on a theory and evidence based understanding of behaviour will increase transparency in the intervention development process and the likelihood that the desired changes in behaviour will occur.

Introduction

Tea and coffee consumption in the UK are becoming increasingly 'on the go'[1]. This has led to a rise in the number of hot drinks sold in cups intended for single use — an estimated 2.5-5 billion single-use coffee cups are disposed of annually in the UK, most consisting of a paper body and plastic lining[2]. Recycling these cups poses a significant challenge. Although technically possible, there are very few facilities in the UK capable of separating the materials for recycling[2]. Due to the difficulty of recycling this material, most cups end up as litter or in landfill contributing to environmental degradation[3]. In addition, the carbon dioxide emissions generated by single-use coffee cups are approximately 1.5 times the weight of the cup[4]. This amount of waste from a single-use item is not sustainable. Therefore, efforts to reduce the number of single-use cups littered or in waste streams are key to more sustainable consumption.

In light of this evidence, University College London's 2019 sustainability strategy is to be single-use plastic free by 2024, aiming to eradicate single-use coffee cups across their university campus by promoting a reuse model. Re-use means extending the service life of a product by using it multiple times, with its intended purpose, before disposal. In this instance, UCL aims to promote the use of reusable cups. Re-use has been identified as the optimal strategy to reduce waste once a product has entered circulation. This is in line with the "waste hierarchy" set out in Article 4 of the EU's revised Waste Framework (Directive 2008/98/EC)[5], which ranks waste management options according to what is best for the environment (shown in Figure 1). This hierarchy recommends waste management strategies that prioritise reducing the amount of waste in circulation, rather than on how to manage it once it is there.

Figure 1. The Waste Hierarchy as set out in article 4 of the revised Waste Framework (Directive 2008/98/EC)



The Waste Hierarchy gives top priority to preventing waste. When waste is created, it gives priority to preparing it for re-use, then recycling, then recovery, and last of all disposal (e.g. landfill, incineration).

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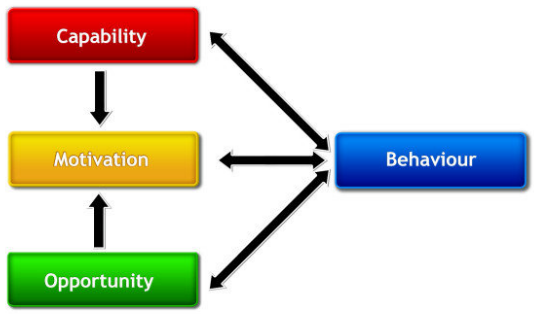
UCL has made previous efforts to promote reusable cup use. In 2016 and 2017, reusable coffee cups were freely distributed to students during their 'fresher's' week with the aim of promoting reusable cup use across UCL catering outlets. In October 2018, UCL introduced the 'ditch the disposable'[6] campaign where a disposable coffee cup charge ('latte levy') was implemented across the campus. Although there was an initial increase in the number of hot drink sales made in reusable cups, this plateaued at an average 20%-25% across all UCL catering outlets.

To further promote reusable cup use across campus, UCL plans to introduce an additional intervention, learning from previous efforts. The first learning is that this seemingly simple behaviour is located within a complex system of several interacting groups, including consumers, suppliers and caterers, operating at various organisational levels within UCL. Guidance from the Medical Research Council (MRC) about developing and evaluating such 'complex' interventions[7], and by others working in implementation research[8] point to the importance of grounding interventions in both theory and evidence, local and more general. This is because in order to decide how to change behaviour (i.e. design an intervention) we first need to understand why behaviour is as it is and what it would take to bring about the desired change. This is facilitated by drawing on theories and models of behaviour change. UCL's previous interventions to increase reusable coffee cup use were not built on a theory- and evidence-based understanding of the influences on behaviour within the UCL context. The current intervention is being developed by a collaboration between several groups at UCL: behavioural scientists[9], the plastic research and innovation hub[10], the sustainability team[11] and the catering team.

Theoretical framework

Shown in Figure 2, the simplest, comprehensive model of behaviour in its context, is the COM-B model[12,13] which posits that for a behaviour to occur there must be the Capability, Opportunity and Motivation to perform the behaviour. Capability can be psychological (e.g. knowledge) or physical (e.g. skills); opportunity can be social (e.g. societal influences) or physical (e.g. environmental resources); motivation can be automatic (e.g. emotion) or reflective (e.g. beliefs, intentions).

Figure 2. The COM-B system - a framework for understanding behaviour



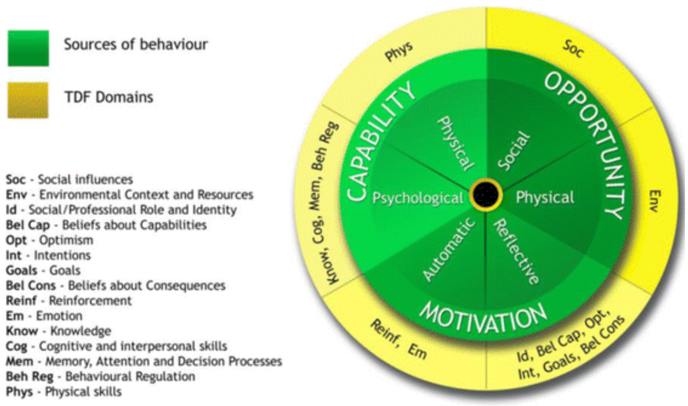
These COM-B components have been elaborated into the Theoretical Domains Framework[14] (TDF), shown in Table 1. It includes 14 Theoretical Domains, representing individual, socio-cultural and environmental factors influencing behaviour (i.e. barriers and enablers). These include people's knowledge and skills, memory, attention and decision-making processes, beliefs about capabilities and consequences, goals and emotions as well as physical and social environmental factors.

Table 1. The Theoretical Domains Framework –14 domains of individual, socio-cultural and environmental influences on a behaviour.

TDF domain	Explanation
Knowledge	An awareness of the existence of something
Skills	An ability or proficiency acquired through practice
Social/Professional role and identity	A coherent set of behaviours and displayed personal qualities of an individual in a social or work setting
Beliefs about capabilities	Acceptance of the truth, reality or validity about an ability, talent or facility that a person can put to constructive use
Reinforcement	Increasing the probability of a response by arranging a dependent relationship, or contingency, between the response and a given stimulus
Intentions	A conscious decision to perform a behaviour or a resolve to act in a certain way
Goals	Mental representations of outcomes or end states that an individual wants to achieve
Memory, attention and decision processes	The ability to retain information, focus selectively on aspects of the environment and choose between two or more alternatives
Environmental context and resources	Any circumstance of a person's situation or environment that discourages or encourages the development of skills and abilities, independence, social competence and adaptive behaviour
Social influences	Those interpersonal processes that can cause individuals to change their thoughts, feelings, or behaviours
Emotion	A complex reaction pattern, involving experiential, behavioural, and physiological elements, by which the individual attempts to deal with a personally significant matter or event
Behavioural Regulation	Anything aimed at managing or changing objectively observed or measured actions

Figure 3 depicts the relationship between TDF domains and COM-B components. COM-B and TDF are part of the 'toolbox'[13,15] of behavioural science frameworks that can be used to understand the influences on behaviour in its context.

Figure 3. TDF domains linked to COM-B components.



Using these frameworks to collect and analyse data about a behaviour targeted for change can be thought of as conducting a 'behavioural diagnosis'. Similar to how a physician might diagnoses an illness to prescribe appropriate treatment, COM-B and TDF can be used to 'diagnose' a behaviour, i.e. identify influences that facilitate or hinder it as a first step to informing interventions to change the behaviour. Both COM-B and TDF have been successfully applied to understanding behaviours relating to environmental sustainability e.g. meat consumption[16] and recycling[17]. As a basis to inform the design of an intervention to promote reusable cup use at UCL, the aim of the present study is to apply COM-B and TDF to understand influences on single-use and reusable cup use.

Research questions

To this end, our study aims to answer the following questions:

1. What is current behaviour with respect to single-use and reusable cups at UCL?
2. What are the influences on single-use and reusable cup use at UCL?
3. What are the views on potential intervention strategies to promote reusable cup use at UCL?

Method

Design

This study is a mixed-methods, two-phased study: 1) Online survey of UCL students and staff to assess current behaviours with respect to hot drink consumption and to explore barriers and enablers to reusable cup use; and 2) Semi-structured interviews based on COM-B and TDF, conducted with a sample of survey respondents to explore barriers and enablers to single-use and reusable cup use in more depth.

Ethical approval

This study has full ethical approval from UCL (project ID: CEHP/2020/579, data protection: Z6364106/2020/02/86)

Phase 1: Survey

Participants

Study participants consist of UCL students and staff. Exclusion criteria are being under 18 years of age, having completed the survey previously and not having sufficient English to complete the survey. 2020 records show UCL has approximately 13,000 staff (including honorary, associate, and visiting staff) and 44,000 students (of which approximately 20,000 are undergraduates and 24,000 are postgraduates). These population statistics were used to calculate a minimum sample size for each group using a Raosoft sample size calculator[18], at a confidence level of 95% and a margin of error of 5% (staff: n= 374, undergraduates: n=377, postgraduates, n=379). As a result, we will invite approximately 623 staff, 628 undergraduates and 631 postgraduates to take part in the survey based on an anticipated 60% response rate for each group, in line with guidance for response rates and responsiveness for surveys[19].

Participants will be offered the incentive of entering into a prize draw for one of ten £50 John Lewis vouchers upon completion of the survey.

Materials

The survey, hosted by Qualtrics, takes approximately 5 minutes to complete and consists of three sections; Section I, 'About you', includes demographic information and questions about current behaviour relating to cup use e.g. "*Do you own a reusable cup for hot drinks*?", "*When you buy a hot drink, how often do you have it 'take-away' as opposed to drinking it in the café*?". Section II, 'Your views about reusable cups', explores beliefs, attitudes and perceptions towards reusable and single-use cups by asking participants to a) rank, on a 5-point Likert scale, agreement with a series of statements and b) provide a written response to the question "*Are there any other reasons influencing whether or not you use a reusable cup?*". Section III, 'What should UCL do?' investigates respondents' views about possible interventions that UCL could implement to promote reusable cup use on campus by a) asking participants to rank, on a 5-point Likert scale, agreement with a series of statements and b) provide a written response to the question "*Do you have any other suggestions for UCL to reduce the use of single-use cups on campus?*".

Initial items for the survey were generated from three sources: a questionnaire developed by health psychologists at Sheffield University's plastics research and innovation hub[20] (funded as part of the same plastics research and innovation project as UCL's plastic research and innovation hub) exploring attitudes and behaviour related to reusable cups; an evidence review of perceptions, behaviours and interventions related to reducing plastic waste[21] and discussions with the UCL Sustainability team to understand what information would be useful to them in planning the intervention. Items were cross-referenced with COM-B and TDF to ensure that no categories of influence likely to be important were omitted.

The survey was piloted for comprehensibility and feasibility with a sample of UCL students and staff including members of the UCL Plastic Waste Innovation Hub and UCL Sustainability. Minor stylistic changes were made to survey items to increase clarity. For example, the term 'on-the-go' was changed to 'take-away'.

The survey was subsequently put onto the digital platform Qualtrics and piloted for usability with the same sample of UCL students and staff and a group of behaviour change experts. In response to feedback, structural changes were made to the survey. For example, the first version of the consent form required participants to tick multiple statements to denote consent. Feedback revealed that this is time-consuming and might deter participants from continuing with the survey. The consent form was simplified to require only one tick to signify consent.

Procedure

We opted for email/online recruitment as it allows the survey to be widely and conveniently distributed amongst students and staff. An invitation email, with the survey link, will be circulated to a selected number of UCL students and staff drawn from a number of mailing lists. In addition, the survey and invitation email will be posted on student Facebook groups (e.g. fresher's/club/society groups). Participants will be required to provide consent before completing the survey. After completion, participants will be asked to leave their email if they are willing to be contacted about follow-up interviews or would like to take part in the prize draw.

Analysis

Section I - 'About you'

To answer the first research question (What is current behaviour with respect to single-use and reusable cups at UCL?) data will be summarised descriptively.

Section II – 'Your views about reusable cups'

To answer the second research question (What are influences on single-use and reusable cup use at UCL?) the mean scale scores will be computed for each COM-B domain and exploratory factor analyses will be conducted to assess the internal consistency of survey items. Responses across participant groups e.g. staff vs students will be compared. To identify domains associated with cup use, a regression analysis will be conducted. Answers to the open-ended question "*Are there any other reasons influencing whether or not you use a reusable cup?"* will be analysed using inductive thematic synthesis in line with Braun and Clarke's[22] guidance (described below). Additional factors influencing behaviour will be generated from these data and summarised as frequencies. These factors will be mapped onto COM-B components of capability, opportunity and motivation.

Section III – 'What should UCL do?'

To answer the third research question (What are the views on potential intervention strategies to promote reusable cup use at UCL?), we will descriptively summarise the extent to which respondents support certain intervention strategies. Free text responses to the question "*Do you have any other suggestions for UCL to reduce the use of single-use cups on campus?"* will be analysed by categorising additional strategies proposed onto Behaviour Change Wheel intervention types and Behaviour Change Techniques.

Phase 2: Follow-up interviews

Participants

From the survey respondents willing to be contacted for follow-up interviews, 15-20 participants will be purposefully selected to ensure an equal split between staff, undergraduates and postgraduates.

Materials

The follow up interviews aim to explore the second research question in more depth (What are the influences on single-use and reusable cup use at UCL?). The interview schedule will be based on COM-B components and TDF domains, with at least one open-ended question per domain, followed by a series of follow-up prompts. The questions will be refined depending on survey responses to explore the most relevant barriers and enablers to single-use and reusable cup use. The interview schedule will be piloted with three students and three members of UCL staff before data collection.

Procedure

Selected participants will be invited for an interview via email. Additional consent will be sought prior to the interviews which will be arranged via email. Interviews will be conducted via Skype lasting an estimated 20-45 minutes. Interviews will be audiotaped and transcribed verbatim for analysis.

Analysis

Interview data will be analysed in a phased approach. First, we will conduct an inductive thematic analysis in line with the approach described by Braun and Clarke[21]. We will then map emergent themes onto COM-B categories and summaries influences with respect to capability, opportunity and motivation.

Step 1: Inductive thematic analysis

A researcher (ALA) will familiarise herself with the data through a process of 'immersion'. This will involve reading all interview transcripts in an 'active' manner i.e. searching for meanings and taking notes of any emergent patterns. ALA will code interview transcripts by highlighting sections of text and generating labels ('codes') to describe their content and group similar codes together to generate themes summarising the shared meaning of similar quotes. Themes will be reviewed and refined in an iterative process and broken down into sub-themes, where appropriate. These results will be reviewed by a second researcher (FL) to assess whether each theme accurately reflects the meaning of the grouped codes and responses. Any discrepancies will be discussed until agreement is reached and theme labels will be revised accordingly; lead author SM will be consulted if agreement is not reached.

Step 2: Mapping emergent themes onto COM-B categories.
Themes will be deductively mapped onto COM-B domains. A COM-B coding guideline, that is, an explicit set of statements of how COM-B is to be applied to our specific data set, will be developed and updated iteratively throughout the mapping process.

Conclusions

This study describes a systematic and replicable method for identifying targets for behaviour change in order to design an intervention to promote reusable cup use across a university campus. Switching to reusable cups represents a sustainable alternative to single-use coffee cups, most of which are lined with plastic. Achieving such behaviour change is complex. Interventions require grounding in both theory and evidence, local and more general. The method presented here can be applied by other organisations to reduce waste from coffee cups intended for single use. The findings of such studies can be used to systematically guide the development of interventions suited for local contexts. The method may also be applicable to intervention designers, researchers and others conducting work aimed at understanding and changing behaviour with respect to waste and other pro-environmental behaviours.

Conflicts of interest

There are no conflicts to declare.

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Notes and references

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Discussion and Next Steps

Discussion and Next Steps

Reflection on the process

The quality of the papers was very high, and with participants reading them in advance there was vibrant discussion and debate. What was lost, the physical interactions and poster session, was more than compensated by what was gained. Not only was the conference more inclusive, because the activation barrier for a question by chatbox is lower, but we also had an automatic record of the discussion via the Blackboard Collaborate technology. Everyone was well-behaved, concentration levels were higher than normal in session 1 of day 2, and it could have been even better if we had more questions in advance, because that would have allowed scheduling and activation of the audience microphones, rather than having the questions read out by the chair.

It turns out that this format is well suited to on-line meetings and we went “from grief and loss to hope” to quote Kerry Burton’s paper [4.3].

Things we’ve learned

The overwhelming conclusion of our 2 days of discussion was “It’s complicated!”. And that Covid-19 is changing attitudes to many aspects of plastics in particular and circularity more generally. A clear future risk is that short term concerns over hygiene will drive an increase in single use plastics and during the conference research came out demonstrating that PPE was ending up in watercourses.

Notwithstanding David Bucknall’s introductory lecture, each of the presentations was from a PRIF grantee. One of the things we learnt is that UCL have the best branding out of us all, as you might expect from such a slick metropolitan organisation. But on a more serious note we all recognised that the proliferation of packaging, with a plethora of formats and materials, was a function of marketing, and that this extreme form of a free market was one of the primary barriers to enabling a circular economy of plastics.

Brands were there right at the start of the plastics industry, so it made us wonder are other classes of materials so associated with trade names and branding? Throughout the discussions we came back to how important plastic packaging is in the definition of brand and its values. We all appreciate that there are often very few differences between the products contained within (carbonated drinks or washing powder for example) but the shape, texture and messages imprinted on the packaging mean we go back to the same product time and again. Self- actualisation through consumption, builds loyalty and drives sales, and drives much of the innovation in the linear plastics economy. “Brands” have always been part of the problem because, as the Rolling Stones sing, “When I'm watchin' my TV, And a man comes on and tells me, How white my shirts can be, But he can't be a man 'cause he doesn't smoke, The same cigarettes as me, I can’t get me no…no no no ….Satisfaction.” [(I Can't Get No) Satisfaction, M. Jagger & K. Richards, ABKCO Music Inc. 1965].

Many papers in this volume demonstrated that as far as “the linear plastics problem” is concerned there are no active deniers. When asked, most people want to change their behaviour; consume and waste less, recycle and reuse more. But sadly there are plenty of people who “don’t care” and through the discussion we worked out that they fall into two classes; those who will never care because they are not concerned (won’t care, or #WGAF), and those who can’t afford to care - because of endemic inequalities they don’t have the economic option to do so.

There are many activists that are already very active in the plastics space, so those of us who are concerned that we develop evidence-based policies need to catch up before poorly thought through policies, based on emotive single-issue campaigns, are enacted. Such policies may well result in unforeseen consequences, at least unforeseen by the groups pushing for them, so it is important that our evidence base is as widely disseminated as possible.

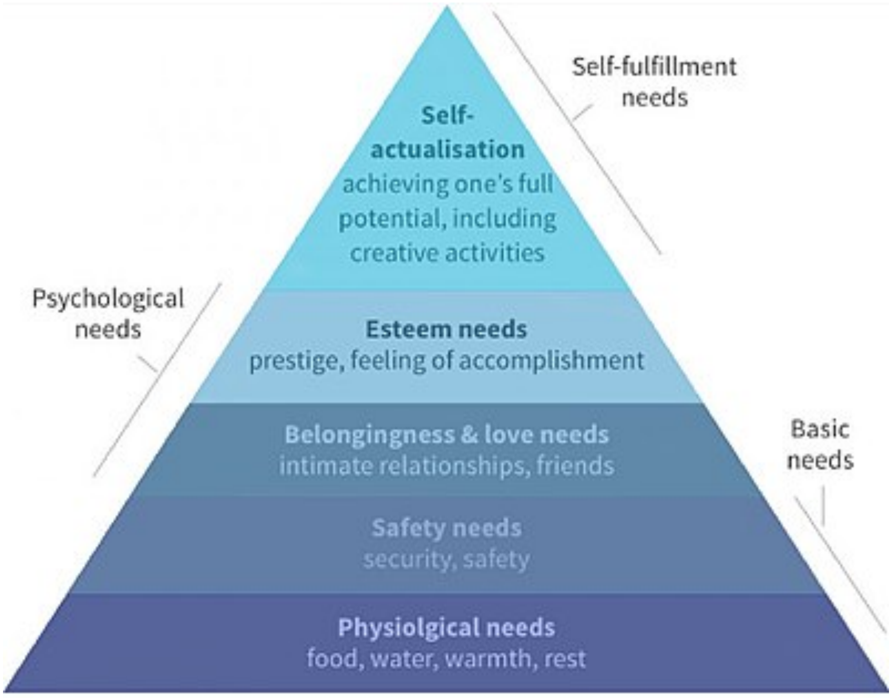
Overall, we learned that very high levels of synergy can be reached by social scientists, engineers and physical & environmental scientists, when they sufficiently engage in the subject and have invested in learning each other's methods. Truly creative and novel ideas occur at the interfaces between disciplines, when different perspectives are brought together in an open and ‘safe’ environment, and as is exemplified in formally in Manchester’s SYSFOCUS [1.4] and informally in many other institutions, we are well on the way to facilitate interdisciplinary and systemic solutions for a plastics circular economy.

We started session 1 with papers focussing on plastics use through Materials Flow Analysis (MFA) & Life Cycle Analysis (LCA). It should be noted the recurrent theme of LCAs throughout subsequent sessions and finding a way to relate MFAs and LCAs to the negative environmental impacts of our current use of plastics requires both a step change in thinking and innovative and transformative actions. This is most obvious in MFA where the concentration is on mass flows but the biggest impacts on the natural world are caused by the numbers of small particles, the so-called microplastics. When considering a change in current practice, a comprehensive analysis of supply chains and their leakages is essential. This determines the full spectrum of impacts, including potential environmental impacts.

Whilst we didn’t have a specific paper on the subject, the research involving human factors demonstrated that language is important to engage, enable, activate and instruct. Linguists and behavioural psychologists have demonstrated that the roles and responsibilities of consumers regarding the end-of-life treatment of products need to be made clearer. For example, the use of transitive verbs (e.g. 'recycle’, ‘compost’) requires a clear agent, in order that the consumer is aware of the action required of them.

One comment that came out of the discussion was the difference between consumers & citizens. Tom Webb insists that we frame the debate around citizens which resulted in a comment that sparked a great debate. “The citizen wants circular and a more sustainable behaviour, the consumer does not want to pay for it...” which will rumble on.

We also concluded from the discussion in session 4 that we need co-creation across the board: youth & older citizens, businesses & policy makers, researchers and end-users. Moreover, we have to be keenly aware of the equality impacts of any change in practice especially where they are brought about by changes in policy, regulation and enforcement. This was borne out in social attitudes to recycling and reuse, it really depends where you are on Maslow’s hierarchy of needs.



Maslow's Maslow's hierarchy of needs
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Whilst at a global and environmental level dealing with plastics in particular, and resource misuse in general, are a basic need - it may well be that for the behaviour of individuals reuse and recycling of plastics are relegated to self-esteem and self-actualisation, especially for those for whom day-to-day life is focussed at the bottom of the pyramid.

Session 2 with its pair of papers on building blocks for bio-based plastics and analysis of biodegradable plastics to provide pathways to plastics from renewable resources [2.1] pose the deep question "are bio-based and/or biodegradable plastics part of the solution or part of the problem?" [2.2]. Our considered response would be "well it depends". Stuart Walker presented some additional time dependent LCA in the discussion session which showed that as the carbon intensity of the energy system declined then there was a crossover between a fossil plastic and its replacement bio-based plastic, the avoided emissions from the renewable resource start to become more important as the energy intensive processes needed to make biobased polymers become less carbon intensive. There will clearly be some niche applications where biodegradability is a desirable property, but because the degradation process results in carbon emissions, it isn't a main-stream solution today.

There was (limited) support for a limited materials set, especially in the highest volume application area of packaging, restricting ourselves 3 polymers, a hard glassy plastic (polystyrene, PS), a hard semi-crystalline plastic (polyethylene, PE) and hard semi-crystalline plastic (poly(ethylene terepthalate), PET) would allow the majority of the range of functions to be covered. Flexible multilayers need a technical solution that allows recycling, and new business models are needed that allow these difficult to deal with, single-use, packaging systems to be replaced.

In the final part of the discussion we asked the question "Are we all still agreed on the plastics use hierarchy?

REDUCE : REUSE : MECHANICAL RECYCLING : CHEMICAL RECYCLING : ENERGY RECOVER

And the answer came back "Yes we are". But what came out most clearly is that business as usual won't work – system innovation is needed. All of the **Things We've Learned** makes it clear that systems level approaches are essential to make progress.

Lots of new questions

The discussions generated lots of new thoughts and questions, for example:

- How many bins do we need? Maximum = 2 - One clean & the other contaminated?
- Medical plastics are a special case and bounded by regulations - is food contaminated packaging the other?

What next?

This volume of papers is not the end of the PRIF process. It is not even the beginning of the end. It is, perhaps, the end of the beginning (with apologies to Winston Churchill). We have brought together partners from industry, businesses, national and regional government, public services, and utilities to work with academics from practically every discipline, natural and social sciences, medicine, arts and humanities. This collective provides insight into the functioning of the plastics system and their continued cooperation is key to developing a circular economy for plastics, whilst recognising that it too is part of a wider material and social system. Socio-materiality, introduced to the group by Boons [1.4], is the perspective that highlights that issues associated with plastics emerge from the interplay of material characteristics and social practices of production and consumption through which these materials are created, transformed, used and disposed of. The combination of engrained use of plastics throughout society and persistent concern about their environmental impacts constitutes a wicked problem: it combines complexity of interrelated social, material and ecological dynamics, uncertainty over risks and consequences of solutions, and divergence of positions over what are legitimate courses of actions to address the issue. No wonder policy is confused and ineffective with many unforeseen consequences.

For these reasons the PRIF grant holders will collaborate over the coming months to produce a White Paper. Our collective outputs will be reported to and used by UKRI, visible to BEIS, DEFRA and other government departments such that the accumulated knowledge base from the wider stakeholder group can be used to formulate evidence-based policy.

A systems perspective is required because plastics are involved across many interrelated and larger systems, e.g. plastic packaging in the food system, synthetic fibers in the clothing system and medical appliances and PPE in the healthcare system. Changing the material involves the technological infrastructure and practices of actors in these wider systems. In developing solutions, reflection is needed that any socio-material solution, when generated and applied in one part of the system, should not create unintended consequences in another part of the system in the present or the future. This is exemplified by a recent report 'It's all on hold' that showed how Covid-19 has derailed the fight against plastic waste. And that the global pandemic prompted some US states to temporarily ban reusable containers and grocery bags and stalled legislation aimed at reducing plastic packaging.

The aim of the PRIF programme was to enable Research Organisations to build a programme of new activities that would stimulate creative thinking across disciplines and explore novel ideas and solutions with potential to deliver more circular economic approaches to plastics manufacture and utilisation, reflecting the research strengths and strategies of the organisation.

In the papers in this volume you have seen multidisciplinary approaches to cleaner and more recyclable plastic alternatives, recycling and recovery processes, better designed products, new service design methodologies to influence citizens (called consumers in the call) behaviour, understanding of plastics materials flows within the economy, and understanding to inform legislation and incentivise behaviour change.

So, we will write that PRIF white paper!

#4evidencebasedplasticpolicy

Dr Rachael Rothman and Professor Tony Ryan
University of Sheffield PRIF project leads and Conference Chairs

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