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Creative Circular Economy Approaches to Eliminate Plastic Waste

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Plastic Sustainability Challenges

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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.

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.

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.

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

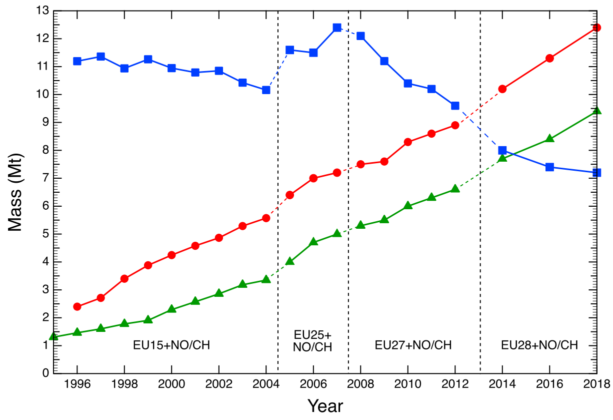

Figure 2: Changes in post-consumer plastic that is landfilled (squares), recycled (triangles) or incinerated for energy recovery (circles) in Europe. Data taken from Plastics Europe annual reports.

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

Please do not adjust margins

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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