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Plastics as a materials system in a circular economy

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Plastics have transformed our modern world. With a range of outstanding properties, they are used in an ever-widening range of applications. However, the linear economy of their use means that a large volume of plastics is discarded after use. It is believed that approximately 80% of the estimated total 6.3 Bt of plastics ever produced have been discarded, representing not only a huge loss of valuable resources, but mismanaged waste is also the origin of an ever-increasing environmental disaster. Strategies to prevent loss of materials resources and damage to the environment are elements of a circular plastics economy that aims to maintain plastics at their highest value for the longest time possible and at the same time improve the economy and prevent detrimental environmental impact. The latter in particular is driving recent changes in policies and legislation across the world that are rapidly being introduced in order to solve these environmental issues. The achievement of a circular economy will require not only innovative technical developments, but also major economic investment and changes to business practice coupled with significant changes in social behaviour. This paper summarizes the complex and highly interrelated technical issues and provides an overview of the major challenges, potential solutions and opportunities required to achieve and operate a circular plastics economy.

This article is part of a discussion meeting issue 'Science to enable the circular economy'.

1. Introduction

The use of plastics in modern society is ubiquitous. Is it in fact remarkably difficult to find anything we use or interact with on a daily basis that is not made

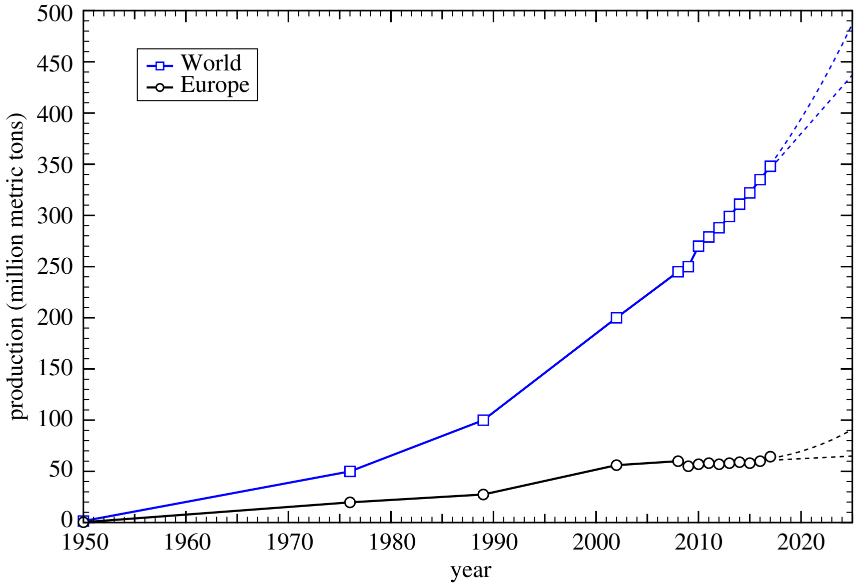

Figure 1. Plot of global (blue squares) and European (black circles) as a function of date from reference [1]. The dotted lines represent predicted production using linear and polynomial fits to the data. (Online version in colour.)

of or contains one or more types of plastic. The total annual production of plastics globally has increased dramatically (by approx. 230 times) since the 1950s to approximately 350 Mt/year (figure 1) [1]. This increased production and use of plastics reflects a greater fundamental understanding and knowledge about their behaviour that has afforded better control of their properties and consequently driven the development of a large number of new polymers. With this increased knowledge has come a greater utilization and exploitation of these plastics. This can be seen by considering annual production of plastics per capita. The global population has increased from about 2.5 billion in 1950 to 7.7 billion people today, i.e. a threefold increase. By comparison, the normalized plastics production, i.e. the mass produced per capita per year averaged across the global population, shows that there has been an almost 50-fold increase in the mass of plastics per capita generated over this time period (figure 2). Although this estimate is not the same for people in high-income compared to low-income countries where use of plastics differs markedly, what it does show is the ever-increasing reliance we have on plastics. While some of the uses of plastics are up to us as individuals, e.g. choosing to use a plastic shopping bag or not, large volumes of plastics are produced and used annually for the benefit of society, such as municipal plastic water pipes, in which case our individual choices are limited.

Clearly, the performance and properties of the various plastics have driven the observed increasing demand and their application. The growth of plastics use has however had unfortunate consequences, the most visible of which is the unlegislated loss of plastics to the environment leading to huge volumes of plastics that have ultimately ended up in the Earth's oceans. The very real prospects that further loss of plastics to the environment will continue to increase environmental damage is understandably driving public outrage and motivating governmental policy and commercial changes in both the use of and methods to deal with waste plastics.

It would be hard to disagree with the benefits that plastics provide when used and disposed of appropriately. However, there remain significant questions as to how to avoid the damage caused by inappropriate loss of waste plastics to the environment. Currently, the life cycle for a majority of plastics used conform to a linear economy approach, whereby the plastics are produced, used once and discarded, which have become known as single-use plastics. This model of usage is the underlying origin of the current plastics pollution problems, which we

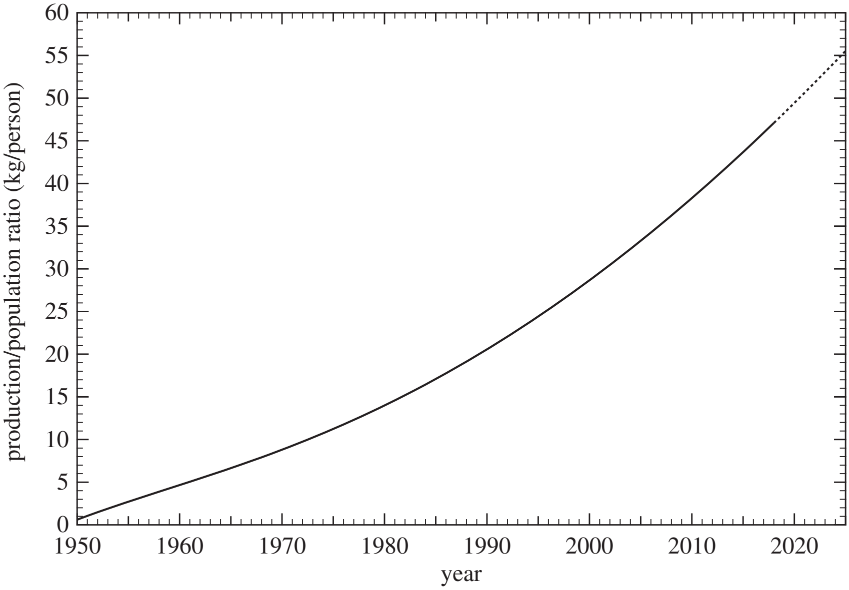

Figure 2. Normalized global total plastics production per person as a function of year. The dashed line represents a polynomial extrapolation of both production and population figures.

are only now just beginning to fully realize. Single use plastics, particularly those used for food packaging, have become the focus of current or imminent bans for production and use in many countries across the world, including the EU and most recently China. Preferable strategies to preventing environmental harm from single-use plastics would be to prevent them getting into the environment in the first place. Such strategies include exploiting their reuse and potentially recovering the resources that the plastics contain, leading to a reversal of the linearity of use that too much of the current plastics are subject to. This circularity of resource flow is at the heart of the concept of a circular economy. This paper explores not only the reasons why plastics are so useful, but also the issues and some of the potential solutions to achieving a circular economy.

(a) What is the circular economy?

The answer to 'what is the circular economy' is not straightforward. This is partly because of the complexity of the concepts it incorporates, but also since the concepts are not only defined in various and often contradictory ways, but is also because they are continually evolving and being redefined [2]. The circular economy can broadly be thought of as an alternative to the current unsustainable linear economic model, which involves circularity of resource flow by preventing loss of material out of the system. However, circular economy models go well beyond simple concepts of recycling as it approaches a system level approach that integrates economic activity with environmental and social sustainability. The circular economy concepts have developed from approaches to sustainability and incorporate ideas where products and materials in the system are maintained at their highest value for the longest time possible, removing reliance on non-renewable resources, designing in reduction of waste from the outset, as well as avoidance and elimination of contamination, toxicity and pollution. Current methods of circularity, such as recycling, can and do reduce damage to the environment and reduce pollution, but an important feature of the circular economy takes this a step further with the intent to repair previous environmental damage. A component of the circular economy model is through use of what is often generically called eco-design, whereby products are designed to last longer, use fewer materials and less energy to produce them, replace scarce materials with plentiful ones (i.e. those that are renewable and sustainable), restore ecological balance in the environment, as well as enable easy disassembly into its constituent materials in order to recover the valuable resources [3,4]. Design concepts for circularity therefore need to distinguish between designs that aim to exploit the durability of the material for reuse, repair and remanufacture, and product designs aimed specifically towards decomposition. The product design also needs to integrate life cycle thinking particularly with regards to energy considerations, as well as take into consideration social aspects that include total product ownership costs [5]. The adoption of a circular economy is also seen as a route to improving other aspects of society, for instance by generating a new labour force needed to reprocess (i.e. remanufacture and repair) goods and materials that would proliferate within the circular economic model [6].

In the context of plastics, achieving a circular economy presents enormous challenges, not least because our current approaches to plastic production, usage and fate generally do not meet most, if any, of the principles of a circular economy. A case in point is the dominance of fossil fuels as plastics feedstocks, which clearly contradicts a key principle of circular economy of only using renewable resources. Other contradictions can be seen with the current fate of plastics after use, i.e. their end-of-life. Even with the rise in recycling practices over recent years, a majority of end-of-life plastics are currently either still sent to landfill or increasingly incinerated for energy-recovery, both practices that not only contribute to damage to the environment in different ways, but also represents an enormous loss of a valuable resource.

To achieve a circular economy of plastics, significant changes to current practices will need to be employed that include new and sustainable approaches to eco-design, reuse, repair and maintenance, leasing and sharing, recycling, and chemical conversion [2,7], quite apart from the necessary social and economic changes that will be required. Several governments, including the EU, local authorities, as well as individual companies have introduced policies that promote the circular economy as an attempt to reconcile environmental concerns against the framework of economic growth. The economic benefits potentially could be huge if fully implemented, with current estimates indicating the circular economy would contribute US$ 1 trillion/yr to the global economy [8].

However, the circular economy concept is not without its critics, and indeed certain schools of thought suggest that because the economy is inherently entropic and therefore linear by definition, it will consequently be impossible to achieve circularity. Equally, the need to account for energy use in the entire life cycle of the plastics within the overall circular economy framework is cited by critics as another reason that circularity is impossible. However, this argument presupposes that future energy use will not be renewable, but recent action globally is demonstrating that renewable energy is a viable alternative to fossil-based power sources. Despite these critics, the ideas and principles of a circular plastics economy are now widely studied, continuously developing and increasingly being implemented across the world, even though there is not always agreement on what it means.

(b) Current waste issues

Despite all the recent changes in policies and implementation of circular economy plans by governments and companies, the practical situation is that waste and pollution deriving from plastics remains a very serious problem. Within many individual countries specific commitments to address plastic waste and pollution problems have been established. For instance, in the UK, WRAP (the Waste and Resources Action Programme charity) in junction with the Ellen MacArthur Foundation (EMF) have brought together government and local authorities, companies, NGOs and citizens to develop the UK Plastics Pack with specific targets to be met by 2025 [9]. These targets aim to eliminate problematic or unnecessary single-use packaging, increase reuse, recycling or composting to 100% and increase the average recycled content across all plastic packaging to 30% or greater. Similar plans have been developed in many other countries, including within most of the 28 European (EU 28) and economic partner countries, i.e. Norway (NO) and Switzerland (CH). The approaches to solving the waste plastics problem are guided by

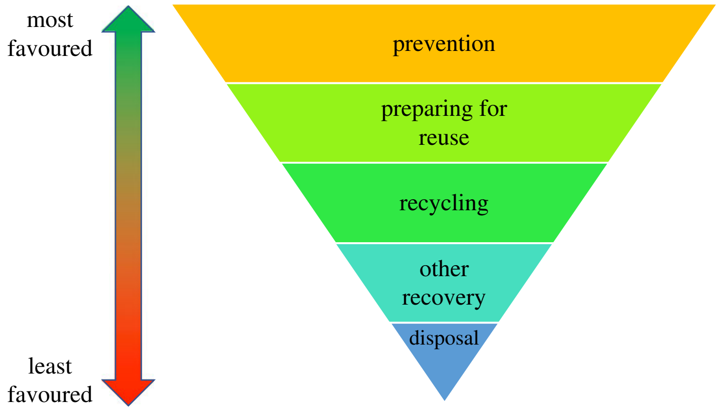

Figure 3. Waste hierarchy of generic approaches for most to least favoured options. Adapted from reference [10]. (Online version in colour.)

the waste hierarchy (figure 3) [10], which reflects the concepts of a circular economy whereby the primary focus is for the plastics to be retained in use for the longest time possible. Although such unilateral efforts will have effects within individual countries, the plethora of approaches to reach the stated targets lead to obvious confusion, particularly for companies that trade internationally. To help address these issues, international action plans are beginning to be adopted, one of which is the New Plastics Economy Global Commitment led by the EMF in collaboration with the United Nations (UN) Environmental Programme, which unites companies, governments and other organizations to address plastic waste and pollution at its source [11]. As of 2019, over 350 co-signatories from GOs, NGOs, companies and universities have agreed to global targets that are similar in extent and target date to the UK Plastic Pact.

While these targets are a direct response to the ever-increasing plastics pollution problem, the question arises as to whether these targets are achievable. To achieve the stated targets, very significant changes are required both in technological approaches as well as economic resources and investment. None of these developments will make any difference without changes to societal behaviour and attitudes, including preventing littering, uptake of reuse schemes, better adoption of recycling schemes, and legislative changes and internationally binding controls among many others.

However, do all these stated targets make complete sense? At present very little plastic waste is composted, but this is one of the three stated methods that are proposed to reduce plastic pollution within the Global Commitment. The reason the majority of the major plastics are not currently composted is simply because most plastics do not decompose in standard compositing systems, since biodegradability is a fundamental requirement to be compostable [12]. Equally, are all stake-holders prepared to make the necessary economic invests required to meet the targets, and even if the investments are made immediately will this allow sufficient timescales for the new industrial plants to be built and become operational? The use of compositing also questions whether compositing is in fact consistent with circular economy concepts, since the plastics are designed specifically to be removed from the resource flow immediately after use, and therefore contrary to retaining the plastics in the system as long as possible.

2. Plastic usage and fate

(a) Why use plastics?

Applications of plastics can be grouped together into different sectors of use as shown in figure 4. While these usage data represent EU 28, NO and CH countries, they are similar to all developed

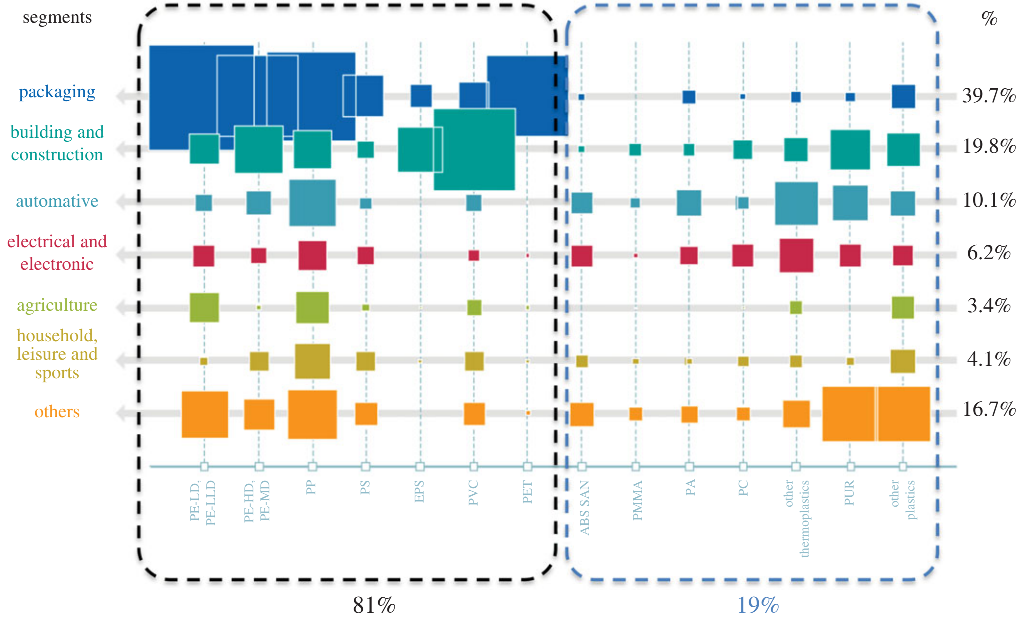

Figure 4. Chart showing use of plastics in various sectors. The percentage of plastics used across the different sectors is shown on the right-hand side. Chart modified from reference [13]. (Online version in colour.)

nations. As can be seen, the largest sector of use for plastics accounting for approximately 40% of annual global production is in 'packaging'. Although a huge range of plastics are known, with hundreds listed in materials databases, the vast volume of plastics that are used are limited to a small number. As shown in figure 4, over 80% of all plastics used are limited to polyethylene (low-density, LDPE and high-density, HDPE), polypropylene (PP), polystyrene (PS and EPS), poly(vinyl chloride) (PVC) and poly(ethylene terephthalate) (PET).

Plastics have become so prevalent because of their range of desirable properties that include their light weight (low density), durability (they don't decompose easily), chemical resistance, relatively low cost, ease of production and processing, safety (they don't break to form dangerous fragments cf glass shards), hygiene (they are food safe and protect the products), low gas and liquid permeability (extends shelf life and prevents food wastage) and massive design freedom.

When considering plastics in packaging, their impact is significant and has huge global implications. Walk into any supermarket and plastic packaging of every description is clearly very evident. These include bottles for carbonated and non-carbonated drinks and fruit juices as well as household chemicals (including cleaning and personal care products), healthcare products, perishable and non-perishable food wrappers and containers, clothes and fabrics, electrical items and even plastic bags to take your groceries home, to name a few. While it could be argued that some plastic packaging may seem unnecessary; for instance, is it necessary to have so much wrapping on children's toys? By contrast, wrapping of perishable foods not only significantly increases the shelf-life of the product, but also protects it from harmful bacteria. The benefits to shelf-life for perishable food items can be seen in a number of examples as shown in table 1. Clearly an optimized packaging system (in these cases flexible plastic packaging) makes a big difference to how long the food remains edible. It also means that food can be sourced from around the world and still arrive in local supermarkets as fresh as when it left the farm it was produced without significant loss. The detail of these food losses is beyond the scope of this current paper; however, it is worth considering the role played by packaging in reducing food losses. Data collated by the Food and Agriculture Organization of the United Nation (FAO) for annual global food losses (table 2) [16] indicate that the percentage of food losses associated with

Table 1. Average shelf-life for various perishable food items with and without flexible plastic packaging. The shelf-life ratio is that for packaged to unpackaged values. Data taken from references [14,15].

food	unpackaged (days)	packaged (days)	shelf-life ratio	package type
banana	15	36	2.4	perforated PE bag
cucumber	3	14	4.7	PE shrink wrap
meat—minced	3	29	9.6	MAP[a]
grapes	7	70	10	OPP[b]

[a] MAP, modified atmosphere packaging.
[b] OPP, oriented polypropylene.

Table 2. Average percentage of food loss by food category. Data taken from reference [16].

food type	percentage loss (%)
fish and seafood	35
cereals	28
fruits and vegetables	50
meat	22
dairy products	19

Table 3. Percentage of total food loss associated with pre-consumer (i.e. production, processing, transport and distribution) and by the consumer for different geographical regions.

region	pre-consumer (%)	consumer (%)
Europe	66	34
North America	61	39
industrialized Asia	69	31
sub-Sahara Africa	96	4
Central, North and East Africa	85	15
South and Southeast Asia	90	10
Latin America	87	13

production, processing, transport and distribution compared to that thrown away by consumers without eating show clear regional differences (table 3). The industrialized nations have lower relative values of loss pre-customer than the developing nations, which is in no small measure due to the use of packaging materials.

A generic life cycle of plastics is shown in figure 5. As indicated, currently once used, the fate of most plastics is either for disposal straight to landfill, incinerated for energy recovery, or in the best cases recycled or to a very limited extent re-used. The timescales of when plastics meet one of these fates of course depends on the use it was applied. At one extreme, the plastics can be limited to use for only a few days, which is the fate of many packaging plastics, through to decades, for instance, in the case of plastics in the construction sector [17]. As the total volume of plastics production continues to increase, governmental and local authority policy changes have changed the percentage of the end-of-life fate of plastics. As shown by the data averaged for the EU 28, NO and CH countries (table 4), these policy changes have driven a reduction in overall landfill rates (several EU countries have almost zero landfill rates) with concomitant increases in recycling and

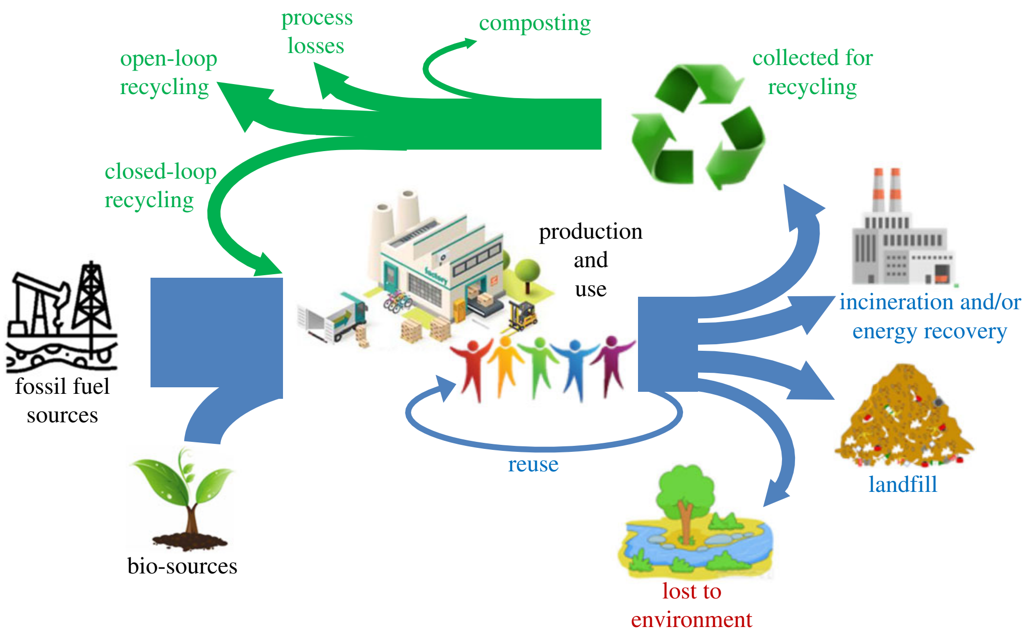

Figure 5. Schematic showing the 'life cycle' of plastics. (Online version in colour.)

Table 4. Data indicating fate of all plastics (mass in Mt and also in percentage) for EU 28 + NO + CH used in energy recovery, sent to landfill or recycled. Figure compare data for the decade of 2006–2018. Data taken from reference [18].

year (total)	energy (Mt) (% of total)	landfill (Mt) (% of total)	recycle (Mt) (% of total)
2006 (24.6 Mt)	7.0 (28%)	12.9 (53%)	4.7 (19%)
2018 (29.1 Mt)	12.4 (43%)	7.2 (25%)	9.4 (32%)

incineration for energy recovery [18]. The reducing reliance on landfill is of course consistent with circular economy policies, but in many countries the rapid filling of existing municipal landfill sites and lack of space for new sites has also played a role in this change in policy. In addition, the clear link between rates of landfilling and inadvertent loss to the environment has moved the public's opinion sufficiently that it is now clearly influencing the thinking and actions of policy makers.

Other factors are also coming into play. For decades, many high-income countries have implemented collection and recycling/recovery approaches for waste plastics. Extended producer responsibility (EPR) schemes were introduced in the early 1990s, and transferred the responsibility of the costs for collection and recycling of waste materials from local governments to the producers [4,19]. The costs of the EPR scheme are usually internalized within the costs of the products. The intent of the EPR scheme is therefore to move towards a circular economy by incentivizing product design from the outset to reduce waste and use of harmful chemicals. Directives within the EU currently allows for individual EPR regulations to be set by member countries as long as they meet a minimum standard set by the EU. This picture is further complicated since different EPR approaches are used in different waste sectors. However, recent policy changes in the EU as it moves towards a circular economy is to harmonize the EPR approaches. The practical problems of individual producers collecting waste from thousands of collection points in any one country has led to the use of third-parties, i.e. producer responsibility organization, who are employed by the producers to organize the waste collection and recycling

[20]. However, not all products globally are covered by EPR schemes since the additional costs make some products uneconomic. This has led some countries to employ other methods, including bans and taxation of products to encourage businesses to move towards a more circular economy.

In addition to the EPR schemes, in the UK, as part of the Producer Responsibility Obligations (Packaging Waste) Regulations 2007, a packaging recovery note (PRN) scheme has been introduced that provides evidence that the waste materials have been recycled. This PRN scheme was meant to help achieve recycling targets set by the Government. The scheme works by allowing the PRN note to be sold on to producers once the waste plastics have been cleaned, decontaminated and recycled. In the current system 1t of recycled (cleaned and decontaminated) plastics is approximately equal to 0.8 PRN. In addition, the UK also operates a Packaging Export Recovery Note (PERN) scheme, which provides a mechanism for exporting municipal waste plastics to foreign countries [21]. The irony of these recovery note schemes is that a PERN is issued on the entire unsorted bale of waste, not the recycled material as required for a PRN. Worse still, 1 PERN is equivalent to 1t of baled unsorted material. Both schemes are perfectly legitimate, but the economic reality is that companies are clearly encouraged to ship unsorted waste material abroad rather than incur the additional costs of properly recycling the waste in the UK. Similar approaches in other Western countries have meant that over decades huge volumes of waste materials have ended up in a number of countries in the Far East and Africa. These countries simply do not have the infrastructure to cope with the massive volumes of waste plastics they receive. It is therefore not surprising that these countries head the lists for being the source of waste plastics entering the oceans (figure 6) [22]. Only some of the plastics pollution emanating from these countries is from their own waste plastic sources, and increasingly it has been noted that the marine plastics pollution contains huge quantities of products that clearly originate from the EU and North America, but released into the oceans via rivers in the Far East, Africa etc. However, recently China introduced an import ban on waste plastics with far-reaching effects globally [23,24]. The exported waste plastics no longer taken in by China were initially taken by other Southeast Asian countries, but very recently a number of these countries, including Malaysia, Indonesia and the Philippines, have also started to close their doors to unsorted waste material. The implications these bans imposed in these waste receiving nations are having is to cause a very rapid change in policy in the exporting nations. Unfortunately, the waste export business will not end overnight, and inevitably the waste will simply be taken by other countries in the immediate future until the waste export from high-income countries stops altogether. In the UK, acknowledgement that the PRN/PERN scheme is flawed has meant the government is rethinking how to change the system, ultimately to achieve 100% recycling rate in the UK [21].

(b) Environmental impact

Beyond the obvious anti-social behaviour associated with deliberate littering, there are various and complex mechanisms for the flow of plastics to the environment [25]. Although macroplastics, i.e. the large, visible waste plastic, are the predominate concern for the general public because it is so visible, it is the micro- and nanoplastic particles, i.e. those not visible to the naked eye, that are perhaps of more concern since they are small enough to interact with ecosystems down to a molecular level. However, the effects that the plastics have on the terrestrial, atmospheric and marine environments are not currently well understood and consequently a subject of increasing research activity [26,27].

Numerous studies have shown that waste plastic that originates on land can transfer via fresh water sources, such as rivers, which then become one of the major sources for the plastics entering the world's oceans [22,28]. In addition, direct release of plastics into the marine environment does of course occur from sources such as commercial fishing [29]. This transport picture is very simplistic since transfer vectors between different environments are interrelated, and it is possible for instance for plastic pollution in the oceans to be redeposited on beaches and terrestrial regions due to wind and tidal activity [30–32].

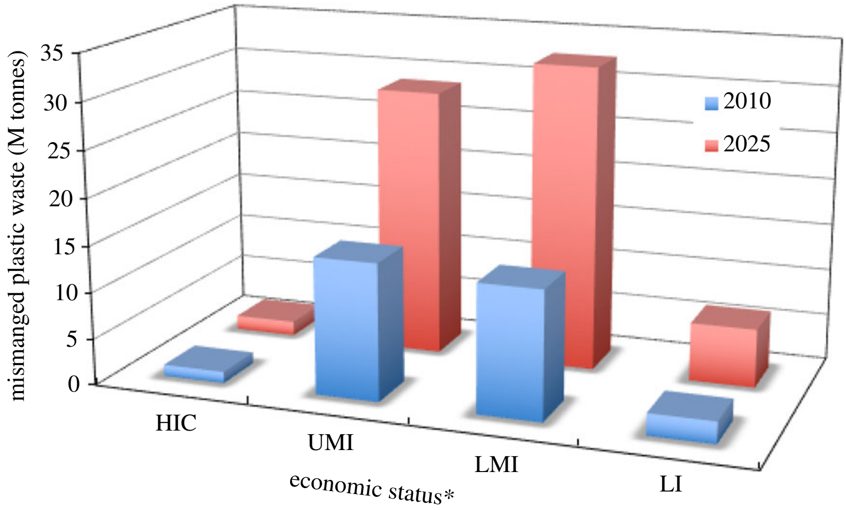

Figure 6. Amounts of annual mismanaged waste plastics based on economic status as defined by the World Bank. Figures for 2010 are compared to estimates for 2025 assuming the same waste management strategies used currently. Data taken from reference [22]. (HIC, high income countries; UMI, upper medium income; LMI, lower medium income; LI, low income.) (Online version in colour.)

It is difficult to measure precisely the loss of plastics to the environment and precise data do not exist for the flow of waste plastic into the oceans, so estimates vary from 4.8 to 12.7 Mt per year [22], which represents about 1.4–3.6% of current global production. A recent study estimates that the total global production of synthetic plastics ever produced is approximately 6.3 billion metric tons (Bt), of which 79% is thought to have been disposed of into landfills [17]. This equates to approximately 5 Bt of plastic that has been disposed of and the remaining 1.3 Bt has either been recycled or incinerated. Based on these numbers and making a crude assumption that a constant rate of 1.4–3.6% of annual production (over all time) has been lost to the oceans,[1] we arrive at a very approximate figure of 70–180 Mt of waste plastics currently in the oceans. These estimates indicate there is around half a year's current total plastics production in the marine environment and despite the efforts of a number of groups to remove the plastic pollution, given the extent of the oceans and the depths at which plastics are found, this plastic is now effectively lost. Regardless of the precise numbers, the volumes are clearly massive and putting to one side the emotive feelings this causes in realizing the problems this is currently and will continue to cause, it should also be pointed out that this is a huge waste of materials resources. Circularity will never be achieved if plastics are continuing to be lost to the environment.

With HDPE, LDPE, PET, PP and PS constituting a majority of all plastics produced, these of course are the ones that are mostly commonly found in the environment. However, plastics pollution is most often classified in terms of their size (i.e. nano-, micro-, meso- and macroplastic) [26] and not their chemical structure or other physical properties. This is most probably because the large easily identifiable macroplastics (i.e. items over approximately 25 mm), gradually fragment and degrade to smaller and smaller particles that make rapid characterization challenging. The macroplastics that litter the landscape and pollute marine environments are highly visible and emblematic evidence of the rising plastic pollution problems, particularly when marine creatures become affected by it. Waste plastic covering previously pristine beaches and creating ocean 'garbage patch' gyres are all too obvious signs of the pollution problem, but this mass of visible plastic represents only a small fraction of the total volume in the environment. Not

[1]The assumption of 1.4–3.6% as a constant loss rate from land to oceans over the extended time period being discussed is likely to be inaccurate because the loss rates to the environment and therefore the oceans are accelerating with time due in part to lack of infrastructure to cope with ever-increasing volumes of plastics produced.

only will plastics sink out of sight if they have densities higher than salt water, but additionally, because of their size, micro- and nano-particulates are not easily seen by the naked eye. Despite the characterization challenges, careful analysis has shown that micro- and nanoplastic particles are widespread across urban and rural soils [33], as well as freshwater [34,35] and saltwater [22,36] environments. What then of the economic impact of plastics in the environment? The data for terrestrial plastics is not available but estimates for effects on the marine environment have been made. These estimates indicate that marine plastics in the oceans cause a reduction of 1–5% in the marine ecosystem productivity [37]. Based on one estimate for the economy of the marine ecosystem to be worth around US$ 49.7 trillion per year (in 2011) [38], the reduction caused by marine plastics is equivalent to an economic loss of approximately US$ 500–2500 billion per year. Put another way, this reduction in marine productivity amounts to US$ 3300–33 000 per tonne of marine plastic in the oceans [37]. With current virgin prices for polyethylenes (the cheapest, but most widely produced plastic) of around US$ 1000–1200 per tonne [2019 prices], the economic cost of the waste plastics in the marine environment far exceeds the costs of producing it in the first place. Further studies into economic impact of marine litter have evaluated the costs associated with removing beach litter, with numbers seemingly varying widely, but estimates of €18–19 million for the UK in 2010 show the not insignificant detrimental impact on the economy from unlegislated litter [39].

The ecological effects of plastics are also still an area that needs much more research to further our understanding. Macroplastics can potentially kill a variety of animals, marine creatures and birds simply through physical entanglement [40] or by starvation resulting from ingestion and gastrointestinal blockages [41,42]. However, cause and effect for macroplastics are much more straightforward to understand compared to the effects of micro- and nanoplastics in the environment. In the latter case, interactions of these small particulates with organic life forms is highly complex and many factors come into play including size, shape (spherical versus fibrous), chemical nature of the particulate surface, and potentially hazardous even toxic additives (including plasticizers, stabilizers, retardants, dyes and pigments) that can leach out of the plastics. Toxic substances that have historically been used in plastics,[2] such as bisphenol A (BPA) and a range of phthalates [43], are known to have adverse effects including endocrine and embryonic developmental disruption as well as reproductive abnormalities [32,43,44]. While negative impacts to life forms have been observed because of the presence of plastics, some microbes and invertebrate have benefitted by exploiting the particulate surfaces as ideal substrates for colonization, including harmful bacteria [45]. Despite these studies, the effects that plastics causes in the environment are still largely unclear.

Attention by the media has recently raised the issues of the potential risks of exposure of humans inadvertently ingesting plastic microparticles by eating fish and seafood. However, eating seafood is almost certainly not the major cause of consumption of microplastics as these exist in the atmosphere as dust in far larger concentrations. For instance, one study comparing microplastic particles in shellfish found that at one extreme, there were over 556 times more microparticles deriving from airborne dust on the food compared to the number resulting from the seafood [46]. Since it is hard to get away from dust, we are almost certainly consuming microplastic dust even when we aren't eating seafood, so it is highly likely that we are all inadvertently consuming microplastics during every meal. So far, there are no indications that any of the ingested plastic has caused any harm to human health, but further study is clearly required.

Remarkably the terrestrial environments have received much less scientific attention than their marine equivalents, despite estimates to suggest that microplastic terrestrial contamination is 4–23 times higher than in the oceans [35]. It is only relatively recently that micro- and nanoplastics as globally important terrestrial pollutants have received much attention, with strong evidence to show that microplastics can interact with terrestrial organisms, such as soil dwelling invertebrates

[2] Additives in plastics are now much more closely legislated compared to some decades ago, and many additives that were used previously are no longer permissible due to their demonstrated toxicity.

and fungi and plant-pollinators, and potentially disrupt their essential functionality in the ecosystem [47]. Sources of terrestrial micro- and nanoplastics either come directly from, for instance, breakdown of agricultural mulch films and soil conditioners (e.g. plastic flakes and foams), or indirectly from non-specific littering, atmospheric particulates [48], and from use of treated wastewater or biosolid fertilizers [35,49]. It is estimated that in Europe between 63 000 and 430 000 tonnes of microplastic enter the agroecosystem every year from biosolids alone [33]. These biosolids derive from sewage treatment plants, but they also contain domestically produced microplastics including fibres from washing clothes and microplastic beads from healthcare products [50]. While biosolids generated at treatment plants are an effective method to prevent microplastics directly entering the water system, despite subsequent treatment a large amount of these particulates remain in the biosolids and subsequently transfer to soils during fertilization [50,51]. The impact these particulates have on the terrestrial organisms are complex and not at all well understood. Of the limited number of studies that have been conducted, effects of toxicity from leaching of additives from the plastics [52], mobility of organic contaminants [53], and changes in soil properties, microorganisms and plant growth have been observed [54,55]. Significantly more research is required to better understand the long-term implications that micro- and nanoplastics have on terrestrial ecosystems and of course the effects on the food chain.

Environmental pollution is clearly a huge problem, not least because of the complexity of the issues. Although individual efforts, such as local beach clean-ups, as well as high profile technologically advanced efforts, such as the Ocean Cleanup [56], are being used to address the problem, not everyone can agree on potential solutions [57]. However, terrestrial and marine pollution issues can only start to be solved when plastics are prevented from entering the environment. This will only occur by collective action in key areas that include increasing knowledge base, technological developments and behaviour changes [58].

3. Plastics recycling

As a very important mechanism within the circular economy to retain plastics within the system for as long as possible, recycling is an area that has seen increasing levels of uptake globally over recent decades. Increased recycling offers potential for economic growth as well as reduction of waste plastics that could end up in the environment. The British Plastic Federation have estimated that extending recycling capacity of plastics will create an additional 25 000 jobs in the UK industry by 2030 [21]. In a recent study, McKinsey & Company argue that both plastics as well as petrochemical companies are ideally placed to push developments of both mechanical as well as chemical recycling [59]. They have estimated that new and profitable opportunities offered by recycling have a predicted annual global profit pool of about US$ 60 billion, 39% of which would derive from growth in mechanical recycling and the remaining 61% from developments in chemical recycling [60]. While mechanical recycling is already a profitable business, this is not yet true of chemical recycling.

The major fate of collected plastics is open-loop recycling (figure 7). Open-loop mechanical recycling, which is sometimes also referred to as cascade recycling, accounts for the majority of recycling of plastics. In such recycling, post-consumer plastics undergo mechanical processes to recover the polymers with as minimal changes to the chemical and physical nature of the plastics as possible. To date, much of the recycled plastics from mechanical recycling is open-loop since it is re-used in different products other than the one they were originally recovered from. A typical example is the large amount of PET bottle recyclate that is subsequently used to manufacture of polyester clothing. Of course, closed-loop recycling, where the recycled plastic is used for its original purpose, i.e. PET bottle recyclate is re-used to produce new PET bottles, is the preferred option for a circular economy, but to date surprisingly little closed-loop recycling is achievable (less than 10%). A significant factor in preventing wider implementation of closed-loop recycling is the potential residual toxic and harmful contamination that cannot be easily eliminated with mechanical recycling. This is particularly true for applications in the food packaging and medical plastics sectors. In situations with traceability and knowledge about the collected plastics and

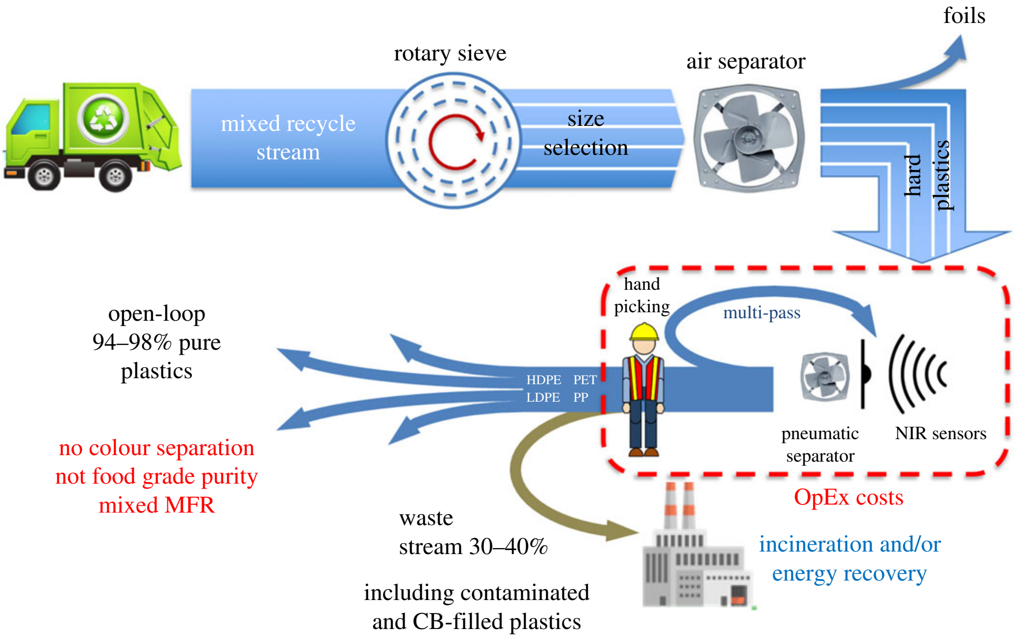

Figure 7. Generic mechanical recycling process of mixed waste plastics streams yielding open-loop recyclates. (Online version in colour.)

its previous use as it goes through the mechanical recycling process is it possible to achieve the level of purity needed for closed-loop recycling. As pointed out by Ragaert *et al.* [61], other terms that are also used in the recycling context such as 'down-' and 'up-cycling' have subjective connotations, presupposing an economic value of the recyclate plastics. Therefore, terms such as cascade recycling, instead of open-loop recycling, inherently imply a recyclate of lower value than the virgin plastic.

(a) Mechanical recycling

Mechanical recycling is the most common and often preferred form of recycling, partly because a mechanical recycling plant is relatively cheap to build compared to the huge investment needed for chemical recycling. This type of recycling exploits mechanical processes, whereby the collected waste plastic is shredded, washed, decontaminated and mechanically sorted into plastics types in a dedicated plastics reprocessing facility (PRF). Most major recycling plants focus on separating out only the four major bulk commodity plastics, i.e. LDPE, HDPE, PP and PET. A number of physical separation processes can be used, including flotation, melt filtration, electrostatic or magnetic separation [61]. By far the most common sorting and separation process in PRFs uses manual and spectroscopic methods. Initial size selection is accompanied with foil (such as packaging films) removal so that only hard plastics are further sorted. In certain PRFs, such as those used for agricultural waste plastics, it is also necessary to wash and also remove solid contaminants, such as soil and rocks, plant and tree matter or, indeed, animal waste, etc., before the sorting process can begin. Repeated use of banks of in-line detectors (most commonly near-infrared (NIR)) coupled with compressed air selectors separate the different types of plastics. Owing to the spectral absorption of carbon black (CB), CB filled plastics cannot be identified easily using NIR and are typically therefore simply removed and added to the waste stream. Even in efficient mechanical recycling plants, up to 30% of plastics cannot be separated or are too contaminated to be recycled, and one of the only options for efficiently dealing with this waste material is incineration. Incineration also has the benefit of eliminating any

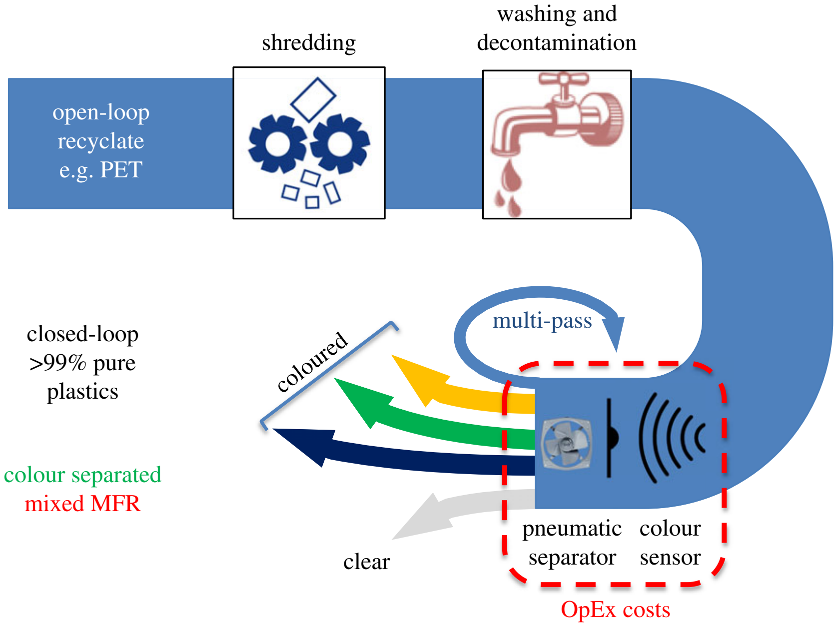

Figure 8. Generic methodology for closed-loop mechanical recycling. (Online version in colour.)

hazardous contamination, such as may exist from medical waste. The output from the mechanical recycling process are streams of plastics that are 94–98% pure. However, while these plastics have reasonably high purity, each type of plastic could still contain mixed colours and other additives as well as a very broad spread of melt-flow rates, i.e. different molecular weights. In addition, much of the recyclates would not meet food grade standards and could therefore not be used directly back in food packaging applications and is therefore a barrier to achieving closed-loop recycling in many packaging applications. Further mechanical recycling is required to provide sufficient colour separation and purification (figure 8). Purities of greater than 99% are possible in such approaches, in part due to starting with a high purity plastic recyclate input. Individual colour separation remains an issue, but separation of coloured recyclate plastics from clear is possible, mostly since pigmented plastics are spectroscopically easily identified compared to clear unpigmented recyclate. The clear recyclate output from these processes can be used when mixed with virgin feedstock for closed-loop recycling.

Detailed analysis from numerous life cycle analysis (LCA) studies has shown that mechanical recycling is in most cases the best waste management option for waste plastics that can be separated. The largest benefits in the LCA are associated with avoiding virgin plastics production from fossil fuels [62]. Despite these benefits, the thermal–mechanical processes used in mechanical recycling and reprocessing cause changes to the properties of the polymers. The most common effect is chain scission along the polymer backbone or in terminal pendent groups to form free-radicals. These radicals can either terminate by disproportionation, leading to a drop in molecular weight of the polymer and increase in polydispersity, e.g. as seen in PP [63,64], or in some cases interchain radical reactions causing cross-linking, leading to an effective increase in molecular weight (MW), e.g. as seen in PE [65]. The effects on the mechanical properties and the melt flow index (MFI) has been studied for a number of polymers. For PP, repeated recycling causes a distinct increase in MFI (i.e. decreases MW) (figure 9*a*) [66]. The effects of repeated recycling on the mechanical properties of PP are modest with only a slight decrease in modulus observed, and other properties such as yield stress and strain to break were seen to be less obviously affected [66]. By comparison, changes caused by recycling to various physical properties are clearly seen in both PA6 [68] and PET [67], where obvious changes in modulus, impact strength, elongation,

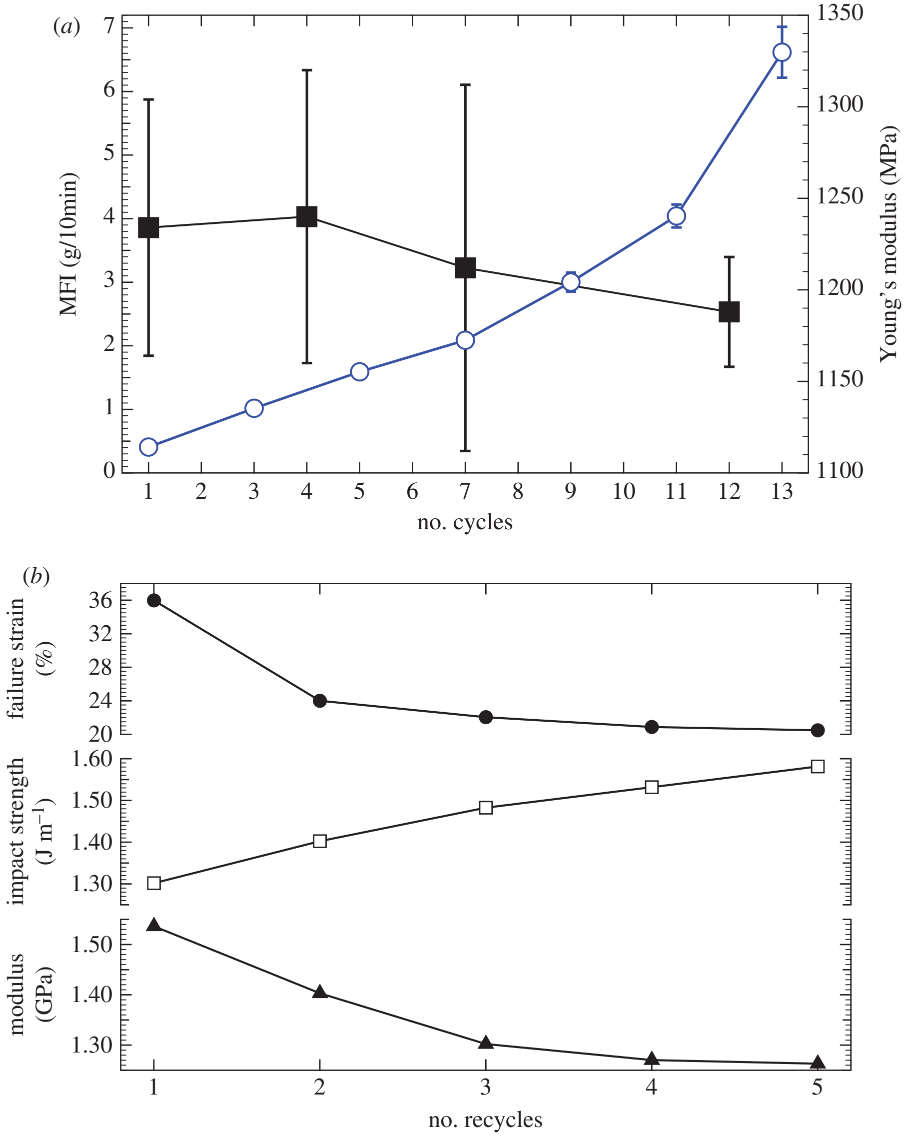

Figure 9. (*a*) Changes to MFI (open circles) and Young's modulus (closed squares) as a function of number of thermal processing cycles for PP, data taken from reference [66]; (*b*) Changes in modulus (closed triangles), impact strength (open squares) and strain to failure (closed circles) for PET as a function of thermo-mechanical processing cycles, data taken from reference [67]. (Online version in colour.)

strain to break, melt viscosity and MFI have all been seen (figure 9*b*). These effects demonstrate the complex nature of the effects on the polymer chain structure that are induced by the thermal–mechanical recycling processes and the effect this has on macroscopic properties. To recover some of these 'lost' properties resulting from the recycling processes, recyclates are mixed with virgin material. Consequently, even in closed-loop systems the percentage inclusion of recycled plastics is relatively low with respect to the virgin material content.

Mechanical recycling is particularly successful in separating mixed plastics streams, but this is not true for plastics either consisting of multiple polymers, i.e. multilayer packaging films or polymer blends, or even plastics that are combined with other materials, i.e. drinks cartons that typically contain multilayers of paper, polymer (often PE) and aluminium. In such cases, simple mechanical recycling cannot separate out the plastics. An additional and significant issue in recycling is the additives in the plastics. Even for a single plastic, depending on its intended end use it may have different types and amounts of stabilizers, pigments, plasticizers, mould release agents, etc., that have been added to produce the visual, chemical and physical properties required. Consequently, from mixed recycling input streams, the separated 'pure' recyclate types of plastic will have a large potential variation in additives. This makes closed-loop recycling extremely difficult if not impossible given the need for returning very specific materials to the processors for remaking products. This in part explains why open-loop recycling is by far the most common outcome from mechanical recycling. The only way to circumvent this is to strictly control the plastics entering the PRF. The ultimate example of that would be, for instance, a manufacturer making melt injected products, where the injection sprue cut offs can be recycled immediately (even without sorting) to make new products. While a trivial example, it highlights the need to track the plastic waste at all stages of manufacture, so that not only can the recyclers determine which polymer it is, but also what was added to it. Given the changes occurring after repeated thermo-mechanical processing, ultimately it would also be useful to know the processing history of the plastics as well.

(b) Chemical recycling

Chemical recycling is the process in which polymers are broken down into either their constituent monomers or other small organic compounds that can be used as chemical feedstocks for repolymerization to new polymers or exploited in other chemical processes. Chemical recycling offers opportunities for exploiting waste to generate value-added products for subsequent industrial applications and commercial products. Several approaches for chemical recycling are possible, with the most common methods being chemolysis, pyrolysis, fluid catalytic cracking (FCC), and hydrocracking. While technologies have been developed for different chemical recycling technologies, to date the economics of these processes have not proved favourable, particularly when compared to petrochemical feedstocks. Some of the economic issues relate to operating at scale and large investment in new chemical recycling feedstock units will be required to achieve the predicted volumes of chemical recycling needed to meet the circular economy targets. Petrochemical and plastics companies, who are well used to building and operating large-scale chemical plants, are seen as the most well placed to invest in these new feedstock units that would integrate with existing petrochemical feedstock units [59]. As discussed above, the economic predictions indicate potentially huge profits of around US$ 37 billion annually can be made from chemical recycling of plastics [60].

Chemolysis is a generic term for a range of depolymerization chemistries, including methanolysis, hydrolysis and glycolysis reactions to form the constituent monomers. Chemolysis cannot be used for all polymers, and is restricted to polymers such as polyesters, most notably PET, and polyamides, such as PA6. The complete or partial depolymerization of PET using a range of solvents can yield not only the monomers, i.e. terephthalic acid and ethylene glycol, but also a host of intermediate compounds depending on the solvent used. Glycolysis is a commercial PET depolymerization process, involving catalysed transesterification reactions at elevated temperature [69] and is exploited by a number of companies [70]. In addition to recovering monomers, glycolysis generates oligomeric products, most notably polyols, which can be used for synthesis of other polymers including polyurethanes, other polyesters and epoxy resins. Sub- and supercritical fluids of water and alcohol are also excellent depolymerization reaction media particularly for condensation polymers, including PET, PA6 and polycarbonate [71].

Pyrolysis is the process of elevated temperature annealing in the absence of oxygen, causing the polymer to decompose into small fragments or even depolymerize [72]. It is the method of choice for plastics that don't easily depolymerize via chemolysis, or cannot be mechanically recycled, such as for polymer blends and multilayer packaging, where separation is not possible. It is therefore more flexible to the range of input waste materials that it can deal with. The pyrolysis process usually operates at around 500°C and slightly above atmospheric pressure (but in the complete absence of oxygen), yielding a mixture of gases, liquids and solid residues [73–75]. However, the decomposition of the polymers is random and therefore different polymers yield different products depending on their composition, decomposition pathway and even the additives that were present. In these cases, post-processing is necessary to separate all the products, making the process only economically viable if undertaken at sufficient scale, implying it can only be successful for the high-volume plastics, i.e. PE, PP, PET, PS and PVC. Unlike the other bulk commodity polymers, PVC is highly problematic for pyrolysis due to the formation of HCl, which is not only hazardous but can also corrode the process equipment [76].

Fluid catalytic cracking (FCC) is a thermal catalytic decomposition process that has a couple of advantages over pyrolysis. Firstly, the resulting products have narrower molecular weight distributions and can even potentially be product specific, and, secondly, the catalyst allows milder reaction conditions to be used, and hence reduces running costs. Two different FCC processes (liquid and vapour phase) have been developed. In the liquid phase FCC, the catalyst in solution interacts with the molten polymer, whereas in the vapour phase process, the catalyst interacts with the gases formed as a result of thermal decomposition. Despite the ongoing research, commercially viable FCC systems do not currently operate. This can be explained for two major reasons, firstly the deactivation of the catalyst by deposition of carbonaceous or inorganic species [77], and the second is associated with lack of reactor technology in which fast catalytic pyrolysis needs to occur.

Hydrocracking is a hydrogen atmosphere catalysed pyrolysis, undertaken at elevated hydrogen pressures (approx. 70 atm) and temperatures around 400°C. The products have a high degree of saturation, with a very low aromatic content, and the process eliminates any potentially toxic products such as dioxins. This has important implications in reducing costs of separation of the products. The significant limitation is of course the cost of the hydrogen and as with FCC potential catalyst poisoning.

Increasing research is exploring enzymatic catalysed degradation of a range of natural as well as synthetic plastics, which are all undertaken under much milder conditions than the other chemical recycling methods [78,79]. Key enzymes for polymer degradation include hydrolase, dehydrogenase, oxidase, lipase and protease. Enzymes use site specific functionality to degrade polymers catalytically either by oxidation or hydrolysis to form monomers and other organic compounds. Many polymers are susceptible to enzymatic degradation including polyesters, polyethers and polyurethanes. Other synthetic polymers such as PE are only degradable enzymatically when their molecular weight is below about 620 g mol^{-1}, although enzymatic activity can be promoted in higher molecular weight polymers if they are oxidized [80]. Another non-biodegradable polymer is vulcanized rubber, although specific bacteria can be used to eliminate the sulfur cross-links (devulcanize) in tyres and latex rubber [81,82]. Companies such as Recircle Ltd are exploiting bacterial devulcanization to enable recycling of vehicles tyres [83]. Since the enzymes absorb on the surface of the polymer particles in order to catalyse the degradation process, the rates of degradation are dependent on the polymer particle sizes. Other factors that affect degradation kinetics include concentration and temperature. The complex nature of the enzymes requires further study to understand and exploit their full potential for polymer degradation in a range of polymers.

So how does chemical recycling compare to mechanical recycling? As shown in table 5, despite significant development, all of the major chemical recycling methods remain as pilot scale operations [84]. However, one of the significant benefits for chemical recycling is the prospect of being able to remove additives, contaminants and toxic compounds out of the plastics, and therefore prevent them being sent for landfill or incineration. The lack of industrial scale chemical recycling can be seen from data published by Plastics*Europe* for the 29.1 Mt of post-consumer waste plastics collected across Europe (EU28 + CH and NO) in 2018 [85]. After sorting, 9.4 Mt of this collected waste, i.e. 32.3%, was sent for recycling, 12.4 Mt was sent for incineration for energy recovery and 7.2 Mt was sent to landfill. Of the 9.4 Mt sent for recycling, the data show that 1.9 Mt was exported via PERN schemes and dealt with outside of the EU, 2.6 Mt was lost due to

Table 5. Comparison of mechanical and major chemical processing methods. Reproduced from reference [84].

process	polymer types processed	output	able to decontaminate?	ability to treat mixed plastics?	technology maturity
mechanical recycling	PE, PET, PP, PS	polymer	no	yes	industrial scale
solvent-based purification	PVC, PS, PE, PP	polymer	yes	no	pilot stage
chemical depolymerization	PET, PU, PA, PLA, PC, PHA, PEF	monomers	yes	no	pilot plants for PET, PU and PA
thermal depolymerization (pyrolysis)	PMMA, PS	monomers	yes	no	pilot scale
thermal cracking (pyrolysis and gasification)	mixed plastics	mixed hydrocarbons	yes	yes	pilot scale

contamination (and subsequently sent for incineration), resulting in 4.9 Mt of recycled plastics, i.e. about 17% of the total that was originally collected. Of that total, less than 0.1 Mt was chemically recycled, which is perhaps not at all surprising given the pilot scale operations of these processes.

(c) All plastics recycling

The source material for mechanical recycling is restricted by only taking collected plastics from recycle bins and therefore does not take more than a limited number and types of plastics. Even with such restrictions (as discussed above) about a third of the input cannot be recycled. To improve recycling rates, recycling of all types of plastics has to be addressed. This is highly unlikely to be achievable using purely mechanical approaches. One study to explore a potential solution is the Lodestar Pioneer Project. This was an industry–NGO partnership research project led by Recycling Technologies and facilitated and supported by the EMF, in which desktop modelling was used to compare a best-in-class mechanical PRF to that of an advanced PRF (a-PRF) [86]. The a-PRF is conceived as an 'all plastics' sorting and recycling facility combining both conventional mechanical recycling with a chemical recycling process. Both the conventional PRF and the a-PRF are able to mechanically recycle 52% of the input, with 5% sent to landfill without recycling (mainly because it contains PVC).[3] Here the systems differ, so that while the remaining 43% output from a PRF would normally be sent for incineration, in an a-PRF this fraction is chemically recycled. Estimates from the modelling indicate that of this fraction about a third would be converted back to plastics, about two-fifths would be converted into other organic chemicals and the remainder would be used as a fuel supply to help power the plant. What this all translates to is potentially an additional 14% of the total input being recycled compared with a conventional PRF, and therefore the equivalent percentage reduction in the amount of virgin feedstock would be required to generate new plastics products. These studies suggest that an a-PRF could increase revenue by 25% compared mechanical recycling alone, in addition to decreasing the payback time of the recycling facility by 11%. Based on these results, a-PRF technology is being commercialized and multiple plants across the UK are planned.

[3]It should be noted that PVC cannot be incinerated in a conventional burner due to the production of HCl(g), and must therefore be incinerated at much higher temperatures than normally used.

4. Incineration and energy recovery

While the use of incineration and energy recovery is not part of the circular economy concept since it does not promote maintaining plastics use or transform waste into an input, it is included in this discussion because it is nevertheless widely used to deal with a vast mass of waste plastics and other materials that cannot be otherwise recycled. In addition, it provides energy that can be used to supplement other energy sources. In terms of the waste hierarchy incineration of plastics for energy recovery is accepted as a higher priority of waste management than landfill (figure 3). It should best be viewed as complementary to recycling, by effectively preventing the necessity for landfill and effectively expediting the treatment of waste plastics that can't be recycled either because of technical, environmental or economic reasons [87,88].

However, the application of incineration of waste to generate electricity does require a steady stream of waste material for the economic model to work. As a number of researchers have pointed out, incineration incentivizes the avoidance of recycling [89,90], and therefore can be considered to be contrary to a circular economy. This contradiction has been recognized as an issue within European policy by referring to incineration as an option for non-recyclable waste [91].

Incineration of waste can produce significant heat output [92], with lower heating values (LHVs) of 42.8 MJ kg^{-1} for PE and 46.5 MJ kg^{-1} for PP. These values are very comparable to common heating fuels that have LHVs of 42.3 MJ kg^{-1} for petroleum and 46.5 MJ kg^{-1} for kerosene. However, mixed household plastic waste is approximately 40% less efficient, with LHVs of 27–32 MJ kg^{-1}, which can be increased to 40.2 MJ kg^{-1} after sorting, but by comparison municipal solid waste has LHVs of only 9.5–10.5 MJ kg^{-1}. Clearly, the best fuel efficiency is only generated from the purest waste streams.

The heat from these combustion processes is mostly used to generate superheated steam to drive electricity generating steam turbines. With power generated in such processes of order 30–120 MW per unit, these are modest compared to conventional fossil-fuel power generators, partly due to the size of the plants [88], given that steam turbine efficiency increases with size [93]. As such the waste recovery systems have to be as simple as possible to make them cost effective, preventing better optimization that has been realized at fossil-fuel power plants [94].

However, a by-product of the incineration process includes the generation of a number of greenhouse gases (GHGs). The major GHGs produced by incineration include CO_2, CO, N_2O, NO_x and NH_3. Clearly, for plastics that are incinerated, they are removed from landfill and therefore prevented from being a source of physical environmental pollution. However, the GHGs emitted do contribute to environmental impact, and serious consideration needs to be made of the implications of these incineration processes. It is therefore necessary to understand the whole system; consequently LCA, especially when coupled with environmental risk assessment (ERAs), is therefore an essential tool to understand the competing processes. Only when considering the factors for the whole system, which includes the collection and transport of the waste materials, construction of incinerators, resource input for the incinerators, environmental impact and of course energy recovery, can decisions be made about which approach minimizes environmental impact. A detailed study of PET showed that for every ton of PET burnt, 2.3t of CO_2 are produced during incineration, but that total is reduced (but not eliminated) by the offset in heat and power generation processes [95]. Interestingly, this study showed that when factoring in all stages of construction, transportation, processing and operation, there is a net loss of CO, NO_x and particulates associated with incineration. At the same time there is net increase in dioxins and heavy metals (including Pb, Cd and Hg), the latter deriving mostly from the transportation and processing of the plastics, not from the plastics themselves. Incineration is not always the best option for dealing with waste plastics, and a comparative study of incineration and recycling undertaken by WRAP showed that generally recycling was better than incineration when considering GHG emissions and the energy balance [62]. However, the reverse was shown to be true if recycled materials could not be incorporated at a high enough volume with virgin plastics or when the recycling process required significant washing. What these studies all show is that the choice of process is never straightforward and requires detailed analysis to minimize adverse impacts.

5. Bioplastics

Bioplastics, by their very name, are often considered to be the panacea for all the world's plastic issues. Exploitation of renewable feedstocks for plastics production, if implemented sustainably, is therefore part of the circular economy concept by reducing reliance on non-renewable resources. While they will undoubtedly be part of the solution in the future, at present and for the medium term, they will probably only play a rather minor part. It will remain to be seen whether they will become as dominant as synthetic plastics have been over the last half century. It is perhaps not fully appreciated that bioplastics derived from natural products were the first man-made plastics, with products such as vulcanized rubber (developed by Charles Goodyear in 1839), linoleum (introduced in 1850s), celluloid (first produced in 1870), rayon (production began in 1890s) and cellophane (invented in 1912). The explosion in use of bioplastics in the late nineteenth and early twentieth centuries is remarkable given it wasn't until the 1920s that Herman Staudinger first correctly described the structure of polymers [96]. While many of these original bioplastics have been replaced by synthetic fossil-fuel derived plastics, recent concerns for dwindling fossil-fuel stocks and issues of sustainability have led to a resurgence of the development and exploitation of bioplastics.

The largest volumes of bioplastics that are synthesized, rather than extracted,[4] are polyesters (table 6), including bio-PET, which is synthesized from ethylene glycol derived from natural sources, but also terephthalic acid (TPA) that is usually derived from petrochemical sources (purely for economic reasons). Although many plastics can be produced from renewable bio-based feedstocks, such as bio-PE, their production is typically very resource inefficient compared to preparing the same plastics from petrochemical sources. Where bioplastics can be efficiently synthesized from bio-feedstocks, their use makes better sense as drop-ins for conventional plastics. For instance, poly(butylene succinate) (PBS), is a biodegradable biopolyester that due to its mechanical properties is a potential replacement for PP. Indeed, there are a number of major companies producing PBS including BioAmber, Myriant, Reverdia and Succinity, from which a range of products including biodegradable bags, short shelf-life food packaging and agricultural films (films and nets) are currently on the market.

Exploration of alternatives to bio-PET have driven studies of poly(ethylene furanoate) (PEF), in part due to its exceptional gas and water permeability compared to PET [98–101], although it is mechanically rather brittle in part due to its structure [102–104]. Nevertheless, Synvina was formed as a joint venture company between Avantium and BASF in 2016 to upscale the bio-production of 2,5-furandicarboxylic acid (FDCA), clearly with a view to realizing large volume production of bio-based products including PEF.[5]

(a) Bioplastics from renewable and sustainable feedstocks

The major start materials for bioplastic synthesis are either sugars, starch, cellulose or castor oil. Depending on the plastic, the choice of feedstock and quantity to produce a unit mass of plastic varies. The main sources of sugar derive from sugar cane or beet, starch from corn, wheat or potatoes, castor oil from the castor beans and cellulose typically from wood, but also lipids, proteins and carbohydrates [105]. All of these natural sources are therefore entirely renewable and if managed correctly they are also sustainable. The quantity of the feedstocks of these natural products required to synthesize different polymers vary, but analysis of all resource inputs for

[4]Synthesis of bioplastics, i.e. from monomer feedstocks, is differentiated from polymers such as natural rubber and cellulose, that are extracted from natural products as whole pre-existing polymers and then chemically modified.

[5]Effective as of Jan 2019, BASF exited the joint venture with Avantium over disagreement on the timing of investment decision for an FDCA plant. In a press release (28 Nov 2019, www.avantium.com/press-releases/), Avantium announced it had secured EU funding for a €25 million FDCA plant.

Table 6. Bioplastics production by type in 2017. Data taken from reference [97].

polymer	production mass (kt)	production percentage (%)
bio-PET	950.5	41.8
biodegradable polyesters	345.6	15.2
PLA	238.8	10.5
bio-PE	200.1	8.8
biodegradable starch	188.7	8.3
PTT	120.5	5.3
bio-PA	97.8	4.3
PHA	75.0	3.3
regenerated cellulose	27.3	1.2
others	25.0	1.1
cellulose derivatives	4.5	0.2

synthesis of various bioplastics has been made [97]. For instance, to produce 1t of bio-PET using petrochemical TPA, necessitates 0.74t of sugar or 0.85t of starch. This would require an input of 4.63t of sugar beet or 5.69t of sugar cane, or 1.21t of corn, 1.85t of wheat or 4.72t of potatoes. While use of sugar and starch feedstocks is renewable, they are also part of the food chain and consequently their use in bioplastics production does raise questions about sustainability (see below).

Other bioplastics that are currently being used or have potential as drop-in replacements for current plastics can be extracted from natural products, including cellulose and chitin. Of these, cellulose is the most abundant natural biopolymer, with vast quantities in natural products. Commercially, cellulose is extracted from wood, agricultural residues, grasses and other plant substances [106]. Commercial use of cellulose has a long history dating back to the nineteenth century, with cellulose derivatives still widely used for a wide range of applications because of their ability to form films in addition to their spinnability [107], coupled with its physical properties [108–112]. Applications include spun fibres, food products, cosmetics, building materials, pharmaceuticals and medical applications. Chitin is the second most abundant natural biopolymer, but it is its derivative chitosan that has been most widely exploited since it is much more soluble than chitin. Estimates suggest there is sufficient chitin and chitosan in the world to replace all petrochemical derived plastics, raising interesting prospects for exploiting these biomaterials. Chitosan is currently used in a number of areas including plant protection in agriculture, filtration binding agents and packaging materials [113]. Owing to the difficulty processing chitin it is less widely used commercially, but research has shown that films for packaging and membranes can be produced [114,115].

Although bioplastics can be exploited as 'drop-ins' for existing fossil-fuel plastics, since the predominant processing method for most plastics is melt processing, the bioplastic substitute has to be compatible with these thermomechanical processes. This means it has to be both thermally stable, but also from a practical point of view it also has to have similar melt flow (viscosity) properties compared to the plastics it is replacing. Often melt processing equipment is optimized for particular polymers, for instance through the design of the screw in a melt extruder. Therefore, is it not always straightforward to simply swap one polymer for another and expect the melt processing to be exactly the same. These machines are expensive and therefore if they need to be upgraded or replaced when switching to processing bioplastics, then this capital cost could be a significant hurdle for many processing companies to switch to using bioplastics.

(b) Degradation, compositing and digestion

Many synthetic polymers will persist in the environment for very long periods of time, which is not surprising, since many of these plastics were designed specially to be durable, mechanically robust, and chemically and biologically resilient. While this means the properties of the polymer can be relied on to maintain their properties during their legitimate use, the fact they don't readily degrade causes the products to persist for a very long time after they have become waste [116]. For these reasons, the concept of biodegradability and compostability of plastics have become very widely explored.

While many bioplastics claim to be biodegradable or compostable (or sometimes both), in reality these plastics do not all readily disappear when you try to compost them. Anyone who has tested the compostability of a biodegradable plastic product at home will have typically found the product looks exactly the same even months (sometimes years) later. The bio-processes required to break down the long polymer chains require specific bacteria that attack and break apart the target chemical moieties in the backbone (see §3b). Some polymers, such as polyesters that contain ester groups, are particularly susceptible to bacterial degradation, but other polymers such as polyolefins are effectively totally unaffected. The bacteria need a specific set of conditions to function efficiently, and, largely, a typical home or garden environment does not provide this. Therefore, commercial compositing and digestion facilities are the only way that the stated inclusion of composting as a mainstream method to deal with plastic waste (see for instance the Global Commitment [11]) can be met. In aerobic composting [117], the microbial degradation process consumes oxygen and produces CO_2 and methane in an exothermic reaction. The heat production gradually raises the temperature of the compost significantly. By contrast, in anaerobic digestion [118], microbial degradation of organic matter occurs in the absence of oxygen, generating CO_2 and methane without any exothermic heat production. Biodegradation of bioplastics has been certified under a number of European standards including EN 13432 and 14995 and ISO 17088 and 11734 [117,118], which specify timescales for degradation after digestion and composting to occur to a size of 2 mm or less within five weeks. Anaerobic digestion capacity (for all waste) in the EU and ETA countries is accelerating, from only three plants able to treat 120 kt per year in 1990 to 290 plants with a capacity of 9 Mt in 2015 [118], and a composting capacity as of 2009 equal to 8 Mt [117].

However, even without deliberate digestion or composting, many biodegradable plastics are susceptible to degradation under normal environmental and atmospheric conditions. These degradation processes do not necessarily cause macroscopic breakdown of these bioplastics, but nevertheless their properties begin to change almost as soon they are produced. The consequence of this behaviour is that for critical structural plastics that are required for engineering applications, such biodegradable plastics could not be used. Another consequence of the properties of biodegradable plastics is that PRFs will not treat such plastics.

As an alternative to polymers that are not naturally biodegradable, oxo-biodegradable plastics have been developed. Polymers such as PE, PP and PS mixed with oxidative catalysts, often manganese or iron salts, are able to degrade in the environment much more quickly than ordinary plastics. The catalyst is designed to cause oxidative chain scission forming hydroxy and carbonyl functionalized low molecular weight chains (typically in the range 5–10 $\mathrm{kg\,mol^{-1}}$), which can ultimately undergo further biodegradation in timescales of less than 18 months. The oxo-biodegradable plastics are also stabilized to prevent degradation in normal operation, providing them with a superior service life compared to unstabilized biodegradable plastics. There is disagreement to the suitability of oxo-biodegradable plastics, with questions as to whether the catalysed degradation of the polymer results in full biodegradability [119]. Detractors of these oxo-plastics, which not only include the EU Commission, but also the EMF among others, argue that the degradation is not fast enough and actually accelerates the formation of microplastics, adding to the damage to the environment. These results have been disputed by the Oxo-biodegradable Plastics Association (OPA), who claim the results in the EU report were biased by commercial conflict and also confuse oxo-degradable and oxo-biodegradable plastics.

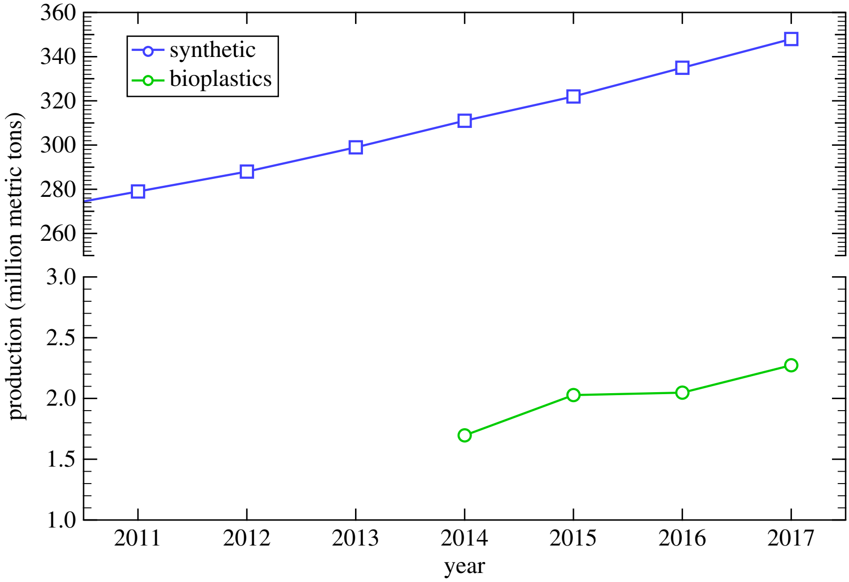

Figure 10. Global production for fossil-fuel derived plastics (blue squares) and bioplastics (green circles). Lines represent guides to the eye. Bioplastics data taken from reference [97] and synthetic production values from reference [1]. (Online version in colour.)

The OPA further claim that oxo-biodegradable plastics are the only way to prevent accumulation of plastic waste in the environment [120]. Based on their own research, the EU commission have now recommended restrictions of oxo-degradable plastics use in the Europe. By contrast, oxo-biodegradable plastics are now mandatory for certain products in Saudi Arabia and 11 other countries in the Middle East and Africa.

(c) A question of scale

The commercial production of bioplastics of all types is increasing, but at present the totals are tiny compared to those produced from petrochemical sources (figure 10). In order to accelerate bioplastics production to a level that they can completely replace or at least greatly supplement petrochemical plastics will require a massive change in resource allocations and production facilities. Based on analysis of resources for production of 1t of biopolymer, estimates of resources required to producing sufficient biopolymers to replace current materials are shown in table 7. While these are simple and admittedly naive examples, the scale of the issues is clear. For the most widely known bioplastics (bio-polyesters, PLA, etc.) their production would require significant amounts of resources that would otherwise be part of the food chain. As discussed above, the Earth's resources are limited, so exploiting food resources for bioplastic production makes no sense. Clearly only bioplastics derived from what would otherwise be truly waste feedstocks represent the only feasible route to increasing production volumes.

6. Is a circular economy achievable?

For most of the era of modern synthetic plastics, their fate has largely been one of a linear economy, i.e. produce–use–discard. As discussed above, this short-sighted attitude has led to the global issues we are faced with at the moment. A circular plastics economy if fully implemented would not only maintain use of plastics for a vast range of applications without having to use a different, potentially more expensive or less optimal material, but also reduce the harm the loss of plastics to the environment is causing. The question therefore is, can a circular plastic economy

Table 7. Resource requirements for bioplastics as replacements for current commodity plastics. Data taken from reference [97].

target polymer	global production (Mton)[a]	replacement polymer	wheat resources per ton (ton)[b]	total wheat resource (Mton)	percentage of global wheat production (%)[c]
PET	33	PLA	3.54	116.82	15.9
		bio-PET	1.85	61.05	8.3
PP	68	PBS	2.11	143.48	19.5
LDPE	64	bio-PE	10.76	688.64	93.5

[a] Production for 2015.
[b] Tonnage of wheat required for 1 ton of biopolymer.
[c] Total global wheat production for 2015 was 736.8 Mt [121].

be implemented and if so what are the hurdles to achieving this? As mentioned above, circular economy policies have been implemented by a number of governments including the European Commission, who instigated an ambitious circular economy action plan in December 2015 to tackle climate change and the environment, while at the same time boosting economic growth, job creation, investment and social fairness [122]. Somewhat surprisingly, in March 2019 the European Commission announced in a press release that ‘Three years after adoption, the Circular Economy Action Plan can be considered to fully completed’ [123]. However, disregarding this somewhat overoptimistic statement and given the obvious reality of the plastic pollution problems that still exist, the EU continues to promote actions leading to a circular economy, including the EU Strategy for Plastics in a Circular Economy [124]. To achieve a Circular Economy in plastics will, of course, require enormous investment in people and infrastructure, but as discussed above the potential economic benefits are immense. On the other hand, not achieving a circular economy also has massive negative impacts on the economy and the environment, which far outweigh any arguments against the costs it will take to reach it.

There are of course challenges to achieving a circular economy, although many technical solutions have already been demonstrated and some even implemented, not all of them have been shown to be economically viable, i.e. as seen for many of the chemical recycling approaches. Remaining technical problems without doubt are something that can be solved given sufficient investment in research and development. What is less certain is how proposed changes will be taken up by the consumers, retailers and producers. This is likely to require changes in policies at both local and regional levels, necessitating potential changes in personal and wider societal attitudes and even lifestyles. However, while many people are willing to ‘do the right thing’, the implementation of often differing policies and approaches to achieving a circular economy, not only between countries, but even within different regions of the same country, is at best confusing. However, the issues of plastic pollution are very definitely a global problem and yet there is insufficient international cooperation and collective approaches being adopted at present that is making any significant difference.

Not only are the policies confusing, but also confusion exists in how individuals should deal appropriately with the used plastics. For instance, labelling on packaging is particularly confusing with at least seven symbols that are used to describe whether something can be recycled or not and whether it is compostable (figure 11). It is quite evident that many people are unsure or simply do not know what these symbols mean and therefore do not know how to deal with the plastic in the correct way, i.e. should they put it in a recycle bin, the waste bin or onto the compost heap. Although the intention of these labels is to inform consumers and provide guidance, the unintended consequence of using so many different symbols has in many cases been quite the reverse. Much better clarity and simplification of labelling would greatly aid the general public in dealing with their waste plastic. Inadvertently putting inappropriate plastics into a collection

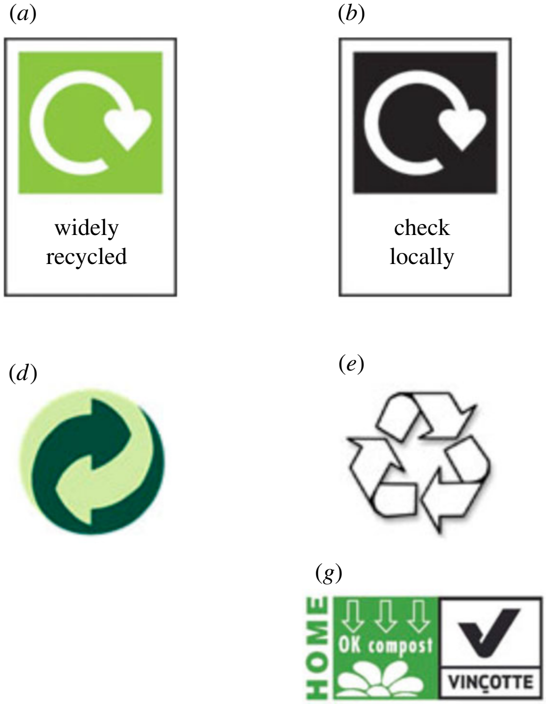

Figure 11. Range of symbols used to indicate whether the packaging recyclability or compostability. (*a*) Indicates packaging is collected for recycling by 75% or more local authorities, (*b*) packaging that is collected by 20–75% of UK local authorities for recycling; (*c*) packaging that is collected by less than 20% of local authorities, (*d*) symbol used across EU that indicates that the producer has made a financial contribution towards recovery and recycling of packaging in Europe, it doesn't necessarily mean this package is recyclable, will be recycled or has been recycled, (*e*) Mobius loop, usually accompanied by a number (1–7) and letters to identify the polymer type. Indicates, object is capable of being recycled, it does not indicate that it will be or has been recycled, (*f*) product is capable of being industrially compostable to a European standard, (*g*) product is suitable to be composted at home. (Online version in colour.)

destined for a PRF is a problem as it is a contaminant and has to be removed, thereby adding to the amount of plastics going to landfill or incineration.

Other technical hurdles preventing increased levels of circularity in plastics include separating the additives (even other polymers) from the base plastic, as well as issues of toxicity and harmful contaminants that prevent higher rates of closed-loop recycling and reuse. These latter factors are of particularly importance in plastics used for food and drinks and medical applications. Only by using chemical recycling is it possible to achieve any degree of separation and potentially detoxification, even if the majority of techniques transform and modify both the polymer as well as the additives. Like the polymer, the additives are a valuable material resource, and any techniques to achieve separation without any chemical transformation are extremely attractive targets. Use of solvents has been explored for plastics separation to selectively dissolve out polymers from waste streams and recover pure polymers. Solvent-based extraction and recycling, benefits from producing recycled polymers without any mechanical degradation, as well as being able to remove additives and other contaminants from the recovered plastics. However, the relatively high processing equipment cost in addition to potentially environment concerns associated with use of non-green solvents means that solvent extraction recycling still faces many challenges to being a mainstream method for recycling [125]. Among the issues to be resolved in this recycling methodology are the potential for thermal degradation during distillation processes employed [126], as well as residual solvent and other polymer impurities [127,128]. Potential future approaches have been demonstrated by a number of university groups [129,130] who have designed fully closed-loop polymer systems. Both polymer systems can be completely depolymerized in acidic solutions back to the start monomers. The process was also shown to allow additives to be easily removed from the resulting monomer solution using conventional separation methods, such as filtering, after which the monomers can be repolymerized to provide the polymer again. At present, these studies have produced specific thermoset plastics and it will be intriguing to see whether the chemistries can be adapted to thermoplastic polymers. While these approaches have only been demonstrated in laboratory scale quantities, they offer tantalizing opportunities to closed-loop recycling.

(a) Reuse and deposit recovery schemes

Reuse is considered to be the second highest level of approach in the waste hierarchy and fundamental to a circular economy (figure 3). A recent report published by the EMF and the New Plastics Economy sets out the case for reusing packaging as a critical component of the solution to eliminate plastic pollution [131]. The EMF report identifies 'refill at home', 'return from home', 'refill on the go' and 'return on the go', as models for business-to-consumer (B2C) reuse.[6] These different models describe the various potential options for the consumer to refill, i.e. reuse containers. In the two 'refill' models the customer owns the container, which is either filled by acquiring refills in store or online ('refill at home') or refilling at a store or refill point ('refill on the go'). The 'return' models both potentially require new infrastructure and logistics, since the 'return from home' involves a drop off and collection scheme, and the 'return on the go' is a purchase and deposit/reward scheme where the return packaging is refilled. Although there are predicted to be environmental and economic benefits for these schemes, there are also significant potential challenges, some are technical and economic, such as the infrastructure questions, but many also relate to the perception, motivation and willingness of customers to adopt any or all of these approaches. 'Return on the go' is essentially a reworking of the household daily milk bottle delivery scheme that is perhaps familiar to many older people. Reuse schemes for glass bottles are of course commonplace particularly in several continental European countries, where deposit schemes for glass bottles are widely used. As seen in Germany, these schemes have had to have government legislation introduced to ensure the system continues to work. The LCA analysis of all these different options will also be intriguing since choice of materials for the packaging and number of reuses has been shown to make big differences on environmental impact [132].

Deposit return schemes (DRSs) or reverse vending schemes, particularly for PET bottles, have been in place for a number of years in limited locations. In the UK, Scotland introduced legislation in 2009 that established the framework for a DRS; however, the consultations for practical implementation, while comprehensive, took until May 2019 before the final details were published [133]. This Scottish DRS will only apply to PET, aluminium and glass drinking bottles so is of limited extent, but should begin to have direct economic and environmental benefits. It may also help affect social attitudes from thinking and treating these as single-use throwaway materials to plastics as a valuable resource.

Use of similar schemes is now a central part of the current thinking for circularity of plastics usage. Given the durability of plastics, reuse is technically straightforward, but bigger questions are raised for instance about aesthetics, i.e. consumer perception about the look of the plastic packaging after multiple uses. People are not overly concerned about glass bottles having a bit of visible wear when used in deposit return schemes, but the question remains if the same will be true for plastic bottles. It is something being actively tested by the company LOOP, a subsidiary of Terracycle [134], that launched a 'return from home' scheme in the mid-Atlantic US and Paris in April 2019, with plans to expand across the US and internationally in the future [135].

[6] Other business-to-business (B2B) reuse models are not discussed in detail in the EMF report.

(b) Product design

As discussed above, many products contain more than one material, and even all-plastic products can contain more than one type of plastic. The reasons behind this are fairly obvious, in that each different material provides a unique property to the product. The complexity that can exist can be seen in, for example, a crisp packet. These packets have been designed to keep the crisps fresh for several months. To achieve this requires preventing gas permeation through the bag, but at the same time it must be lightweight, flexible, tear and puncture resistant, food safe and also allow for labelling to be applied to it. The end result is crisp bags that are multilayer laminates, each layer of which has a very specific function, including structural integrity, preventing oxygen gas permeation, adhesion between layers, surface coating and food stabilization [136]. Such mixed polymer or even mixed materials systems make them impossible to recycle mechanically and in many cases challenging for many chemical recycling routes. Materials that are integrated together to make a product, such as for a vacuum cleaner [137], can be disassembled or broken apart sufficiently to separate the different materials, but not everything can be mechanically recycled and as with highly engineered crisp packets their fate is typically for incineration.

Given that a large fraction of the products' environmental impact is determined by the design, it is hardly surprising that product design is changing rapidly to meet the challenges of a circular economy. Design principles such as eco-design, life cycle thinking (LCT), design for sustainability (DfS), design for remanufacture (DfM), among others, are being developed and implemented by businesses to meet these challenges [5,138]. Clearly the end use of the product must be instilled into the design process from the outset, because designing a product for reuse schemes may have very important design requirements to something that will be recycled. Despite the differences in design approach, a critical feature underlying all of them is the use of new or novel design methods to maximize the material value in the system for the longest available period. As such, whatever the approach, the key element is to 'design out' waste from the outset.

7. Future prospects

While not in any sense a comprehensive review, this paper does provide an insight into many of the current and future potential technical and engineering solutions to achieving a circular economy and the implications plastics have on the environment and global economy. It can be argued that beyond a better understanding and optimization, at least at the laboratory scale, there are few technical issues left to solve, and that many of the bigger challenges come down to economic factors and social behaviour. To put it another way, *plastics aren't the problem, humans and what they do with plastics are the problem*.

Currently, plastics are perceived to have little value, and therefore the expectation is that all plastics should cost as little as possible and once used can be discarded as they are cheap materials. This attitude has resulted in the current linear economy for plastics. This has in part come about because production of fossil-fuel derived polymers, such as PE and PP, have been optimized so much that their bulk costs are incredibly low. Consequently, any post-consumer processing means that the recycled plastics cost more than virgin material. Unfortunately, many consumers are not prepared to pay for the extra cost of recycled plastics over that of the virgin material. Indeed, anecdotally, many people seem to think that simply because the plastic has been recycled, it should be cheaper.

What is absolutely clear is that perceptions and attitudes need to change, and in some cases change dramatically, before real progress can be made to achieve a circular plastics economy. Plastics are not only wonderful materials, but they are also a valuable resource, and it seems nonsensical not to exploit them as such. Clearly, if plastics are sent to a landfill, which large amounts still are, these plastics are lost as a resource and they do not meet any of the criteria for the circular economy. In fact, as discussed above, they may start in landfill sites and still cause environmental damage. Landfill therefore shouldn't even be an option for dealing with plastics, they should at the very least be exploited for the chemical reservoir that they contain. If the polymers can't be recovered in any way, then they should act as a feedstock for generating other useful chemicals via chemical recycling or in the last option as a fuel for energy recovery, in the full understanding that without proper control this energy source will contribute to greenhouse gases. In some cases, such as contaminated plastics for instance used in hospitals, incineration is the only safe way to currently deal with the waste plastics; however, this should not stop novel approaches to finding alternative methods to deal with these plastics. Indeed, successful initiatives such as the PVC Recycling in Hospitals scheme initiated in Australia, which is now also operating in New Zealand (with trials begun in other countries including UK), have found innovative ways to recover and recycle the huge volumes of single-use plastics used in hospitals [139].

Behavioural change is also an important part of the solution. Our modern society has moved a long way from even a generation ago where more value was placed on commodity items we bought and a much lower reliance on single-use items existed. While we shouldn't be trying to turn back the clock, society as a whole must collectively adopt lifestyles that have a net positive effect on the planet. To achieve this, a much better appreciation and therefore education of everyone in society will be required. Many NGOs, companies and charities, among others, have education programmes for schools and the wider public to address just this lack of knowledge [140–142]. Innovative approaches to education approaches are likely to make the most significant impact, particularly given the influence and use of social media in modern society. Clearly educating the youngest children will ultimately have the greatest impact long term, but it is important that everyone across the age spectrum understands what the problems are and how they can contribute individually and collectively to the solution. At the moment, many people want to 'do their bit', but confusing and sometimes contradictory information is being disseminated, preventing these people from acting appropriately.

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