

Review

The Critical Importance of Adopting Whole-of-Life Strategies for Polymers and Plastics

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Abstract: Plastics have been revolutionary in numerous sectors, and many of the positive attributes of modern life can be attributed to their use. However, plastics are often treated only as disposable commodities, which has led to the ever-increasing accumulation of plastic and plastic by-products in the environment as waste, and an unacceptable growth of microplastic and nanoplastic pollution. The catchphrase “plastics are everywhere”, perhaps once seen as extolling the virtues of plastics, is now seen by most as a potential or actual threat. Scientists are confronting this environmental crisis, both by developing recycling methods to deal with the legacy of plastic waste, and by highlighting the need to develop and implement effective whole-of-life strategies in the future use of plastic materials. The importance and topicality of this subject are evidenced by the dramatic increase in the use of terms such as “whole of life”, “life-cycle assessment”, “circular economy” and “sustainable polymers” in the scientific and broader literature. Effective solutions, however, are still to be forthcoming. In this review, we assess the potential for implementing whole-of-life strategies for plastics to achieve our vision of a circular economy. In this context, we consider the ways in which given plastics might be recycled into the same plastic for potential use in the same application, with minimal material loss, the lowest energy cost, and the least potential for polluting the environment.

Keywords: plastics; polymers; reuse; recycling; microplastics; nanoplastics; whole-of-life strategies; life-cycle assessment; sustainable polymers



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1. Introduction

There is a vast range of different plastics or polymers, which have a correspondingly wide range of applications. The obvious everyday uses of plastics appear in packaging, coatings, adhesives, fabrics, transportation and construction. These often single-use commodity applications account for most plastic production by volume. However, it is their less obvious uses in biomedicine (polymer therapeutics, drug delivery), organic electronics (polymer semiconductors, resists) and nanotechnology that have seen plastics become an essential yet unnoticed part of modern life. The problems associated with plastic misuse, plastics in the environment, the growth in microplastic and nanoplastic pollution, and plastic reuse, repurposing and recycling have deservedly attracted a lot of recent attention.

Short-term, single-use plastics, as used in packaging and throw-away cutlery, plates and cups may soon be “legislated away”, although their legacy persists. Other longer-term single-use finite service lifetime applications, such as coatings, paints, and adhesives remain. Significant reports commissioned by the American Chemical Society [1], the Association for the Advancement of Science [2,3], The Royal Society of Chemistry [4], the Australian Academy of Technological Sciences and Engineering [5] and CSIRO [6], among many others, emphasize the lack of sustainability inherent in current production and the imperative for implementing effective whole-of-life strategies for plastics or polymers.

Unfortunately, we cannot wait for absolute solutions, we have to progress, in the full knowledge that any path taken may need to change at short notice, and despite the

potential “loss of face” for the proponents of those paths. We also need to be aware of, and be quick to curtail, technologies that may mitigate the immediate concerns, but result in intractable long-term problems. The best way forward will often not be the most economical in the short term.

It is thus of critical importance to develop recycling methods, both to deal with the legacy of plastic waste and to implement effective whole-of-life strategies for the use of plastic materials. This is recognized by many, as evidenced by the dramatic increase in the use of terms such as “whole of life”, “life-cycle assessment”, “circular economy” and “sustainable polymers” in the scientific and broader literature. However, an issue the authors have encountered in putting this document together is that these terms can be interpreted in many ways. We, perhaps naïvely, started with a belief that a circular economy with respect to plastics should relate to the way a given plastic is recycled into the same plastic for potential use in the same application, with minimal material loss and at a low energy cost. A whole-of-life strategy must end in rebirth. We were quickly disillusioned by our perusal of the literature, which indicated confusion with closed-loop recycling. Nonetheless, in this review, we assess the potential for achieving our vision of a circular economy.

2. Polymers and Plastics, Some Definitions

A polymer is defined by IUPAC as a substance composed of macromolecules [7]. A macromolecule is defined as a molecule of high relative molecular mass, the structure of which essentially comprises the multiple repetitions of units derived, actually or conceptually, from molecules of low relative molecular mass [7].

There is no IUPAC definition of plastics. Plastics are defined by the ISO as material that contains, as an essential ingredient, a high polymer and which, at some stage in its processing into finished products, can be shaped by flow [8]. The term “plastics” is an abbreviation of thermoplastics. It embraces materials formed from all forms of synthetic polymers and bio- and bio-based polymers but does not include cured thermosets. Plastics typically go under the same names as the polymers of which they are principally composed. Thermoplastics are polymers that are composed of non-crosslinked macromolecules held together by nonbonded interactions, such that they can be thermally transformed and retransformed through a moldable, malleable state. Thermosets are polymers that have been cured or crosslinked and, notwithstanding advances in the field of vitrimers or dynamic covalent polymers [9], are, in most circumstances, not thermally remoldable. A thermoset plastic is a plastic that can be cured to form a thermoset. Thermosets appear, for example, as the matrix resin in fiberglass and carbon-fiber composites, and as the crosslinked rubbers found in tires and gloves. Thermosets cannot be easily reprocessed and are thus more difficult to reuse or recycle. Bakelite, often considered to be the first synthetic plastic, is a thermoset.

In developing whole-of-life strategies, the various plastics should not be treated together as a class of materials. Different plastics can have very different chemical, physical and mechanical properties, and each presents a different range of benefits and issues. The major types of plastics, in terms of chemical composition, that are most often discussed in a recycling context include high-density polyethylene (HDPE), low-density and linear low-density polyethylene (LDPE, LLDPE), polypropylene (PP), polystyrene (PSt), poly(vinyl chloride) (PVC), poly(ethylene terephthalate) (PET), and “other”. In this context, “other” would include polyurethanes, nylons (polyamides), polycarbonates, polyesters other than PET, and acrylics. Each of the plastics embraced in the “other” category is also a class of polymer rather than a specific material. Moreover, the major plastics (HDPE, LDPE, LLDPE, PP, PVC, and PET) each come in a wide variety of grades that differ with respect to molar mass, molar mass distribution, detailed composition, the presence of various additives, and specific architecture that give rise to the properties required for the intended application. Some plastic products are composed largely of a single form of plastic (e.g., PET beverage bottles, HDPE milk bottles). However, many applications call for multiple types of plastic

used in combination as blends, composites, or multilayer laminates. The complexity is driven by the property requirements of the intended application (physical properties, mechanical properties, barrier properties, appearance, cost). Petroleum-derived plastics are also often used in combination with bio-based polymers, for example, in cotton-polyester (PET) fabrics.

What to do with plastics once used (or several times used)? The most historically common practices have resulted in polluting the environment and sending them to landfills; both have obvious problems and are now recognized as unacceptable by most people. It has been estimated that, as of 2015, 8300 million metric tons (Mt) of virgin plastics had been produced. This resulted in approximately 6300 Mt of plastic waste. Of this, around 9% was recycled, 12% incinerated, and 79% ended up in landfills or the natural environment [10]. The numbers may vary from country to country, and will have changed in magnitude since 2015, but the fraction that is recycled remains small [11].

A recycled plastic is one that is sorted, purified, and reprocessed to provide a material with properties similar to those of the virgin plastic, such that it can be used again in its original application. In closed-loop recycling, this is achieved with minimal material loss. We distinguish recycling from down-cycling, in which a sorted, cleaned plastic is reprocessed to have inferior physical and/or mechanical properties, making it unsuited for its original application. A reused plastic is one that is reprocessed to be used in another application. Often, it is a product formed from mixed plastic waste where direct recycling is not possible. It may also be a plastic that has degraded to an extent that makes mechanical recycling impracticable.

3. Plastics Recycling

A summary of publications per year on the concepts of plastics recycling, biodegradable plastics, sustainable plastics, micro- or nanoplastics, and plastics and the circular economy is provided in Figure 1. Plastics recycling has been a topic of marked interest since 1990; however, publications on recycling have doubled over the last 5 years. Publications on biodegradable polymers and sustainable polymers have been steadily increasing and, again, have shown greater growth over the last 5 years, which is consistent with the appearance of the term “circular economy” used in the context of plastics, and the more widespread appreciation of the microplastic/nanoplastic problem.

Each of the major plastics (HDPE, PP, PSt, PVC and PET) can, in principle, be recycled using a mechanical recycling process, if they can be obtained in a relatively pure state in terms of composition (free of other plastics and additives) and grade [12]. Thus, there are relatively high levels of mechanical recycling of beverage container PET and milk bottle HDPE, both of which have very low levels of additives and can be obtained in a relatively pure state. Limited mechanical recycling is also conducted for unplasticized PVC, PSt, and some grades of PP. The cost of mechanically recycled plastics is often similar to or slightly higher than that of virgin petroleum-sourced plastics. Much of the cost of recycled plastics is associated with sorting and cleaning the post-consumer feedstock [13]. Substitution scandals, whereby cheaper virgin PET is sold as recycled PET, have been reported and create an imperative for trackable plastics (see Solutions) [14]. For PET, the issue of limited moisture-induced or oxidative degradation can be addressed by blending recycled and virgin PET, or through the use of solid stating or chain extender technology [12,15]. There is then a requirement (that should be mandated) for continuous monitoring of the quality of recycled PET, both for the physical and mechanical properties and the levels of additives/impurities/toxins that may be incorporated or formed and could accumulate through multiple recycling steps [16–19].

Efficient chemical recycling by depolymerization into monomers is also possible for many plastics [20–22]. Thus, PSt and poly(methyl methacrylate) can be converted to their respective monomers by thermal unzipping at high temperatures. Polyesters, polycarbonates and nylons can be transformed back to the monomers used for their manufacture by hydrolysis, alcoholysis, glycolysis, or hydrogenolysis [15,23,24]. These

forms of chemical recycling are technically feasible and can produce quality monomers that are indistinguishable from those derived from petroleum feedstock. However, the cost of monomer production by chemical recycling is bound to be significantly higher than that of petroleum-sourced monomers.

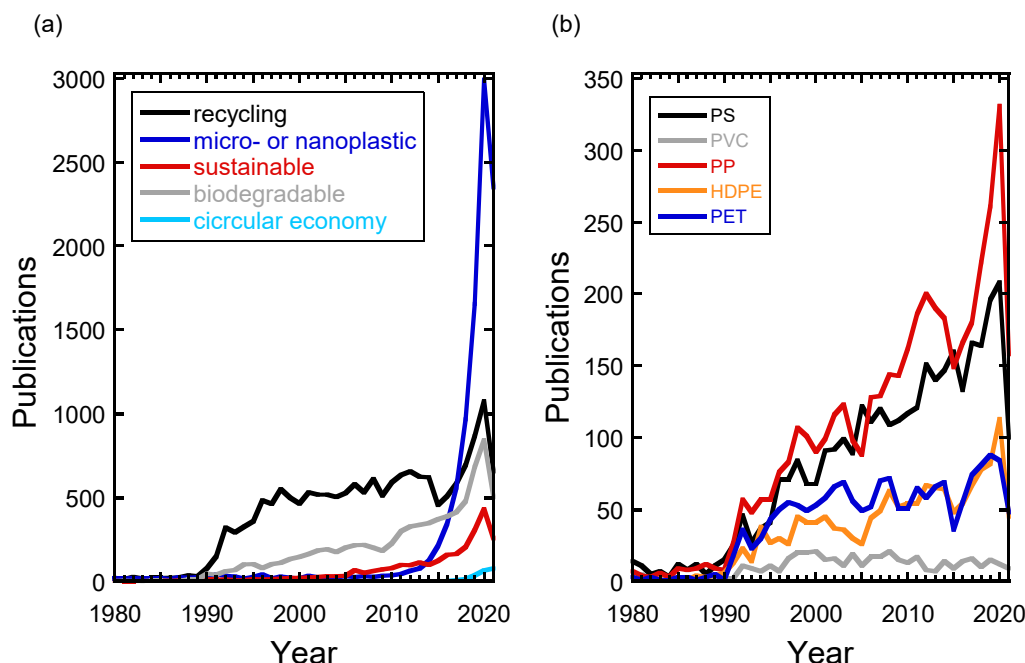


Figure 1. (a) Publications per year on the concepts of plastics recycling, biodegradable plastics, sustainable plastics, micro- or nanoplastics, and plastics and the circular economy, and (b) publications per year on the recycling of different plastics. The topics are not mutually exclusive (a paper may appear in more than one category). Based on a ScifinderTM search conducted on 2 June 2021.

Pyrolysis and hydrothermal treatment both provide routes for the conversion of plastics to a petroleum feedstock [25–30]. One great advantage is that the processes can be applied to most plastics, whether in pure form, as part of a mixed plastic waste stream, or even a plastic/biomass waste stream. The process appears reasonably efficient for polyolefins (Figure 2). Poly(methyl methacrylate) and polystyrene depolymerize to monomers. Cellulose and lignin provide high char yields. The need for sorting plastics (in particular, to remove PVC) before pyrolysis is, however, evident. These processes are also called chemical recycling. In principle, the petroleum feedstock can then be subjected to a process similar to those used in petroleum refining to produce monomers. The efficiency for recycling a given plastic back to the same plastic would be very low (it may not have been achieved). It is most expedient to combine the petroleum feedstock that is produced with fossil fuel-derived feedstock. However, the process is energy-intensive. Currently, the cost of producing petroleum feedstock by chemical recycling strategies is substantially greater than production from fossil fuel resources, but this may change as fossil fuel resources become scarcer, and the costs of non-renewable and recyclable carbon are recognized. Pyrolysis is currently the method of choice for recycling mixed polyolefins (e.g., PE, PP) [30].

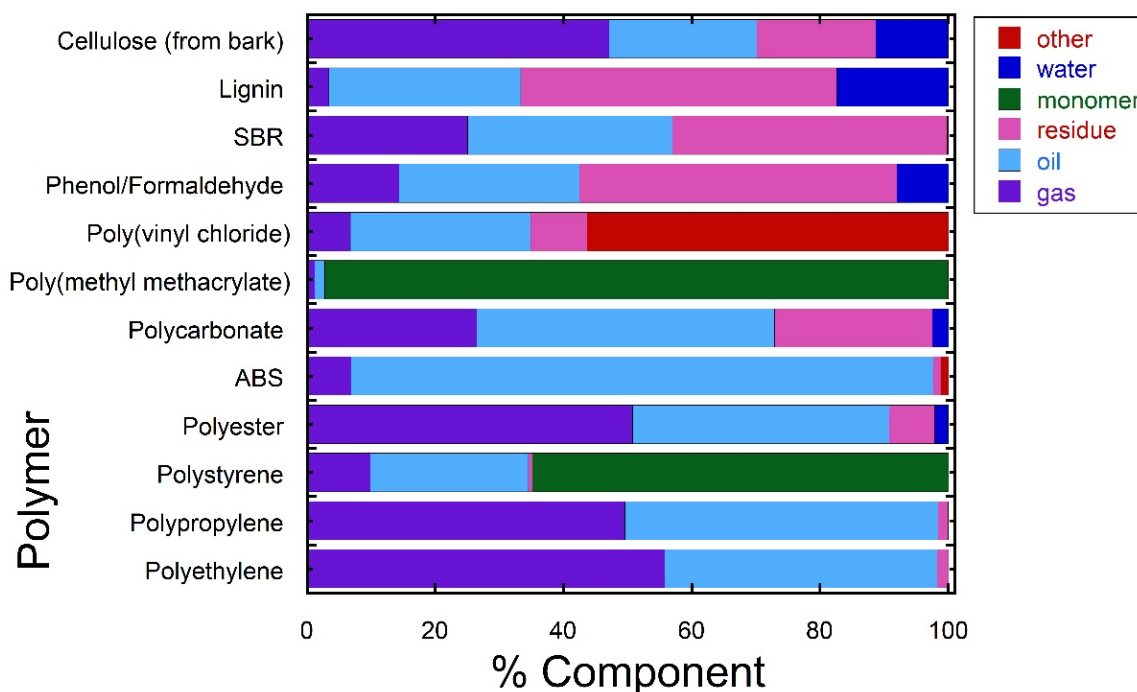


Figure 2. Distribution of products from non-catalytic pyrolysis of various plastics, lignin and cellulose at ca. 750 °C. “Other” is toxic gases, hydrochloric acid in the case of poly(vinyl chloride), and hydrogen cyanide in the case of SBR. Figure constructed from data provided by Hees et al. [30] and attributed to Kaminsky [31].

The uncontrolled burning of plastics is unacceptable. However, incineration of plastics might be a solution, if conducted in a high-efficiency incinerator to produce CO₂ and H₂O, with effective energy recovery and CO₂ capture, sequestration and usage (CCS and CCU). Processes for catalytic hydrogenation [32–37], or electrochemical [38–46] or photochemical reduction [47–49] of CO₂ to produce methanol, a petroleum feedstock and even specific monomers (selective electrochemical reduction of CO₂ to ethylene with >70% Faradayic efficiency has been demonstrated on a laboratory scale [50,51]) constitute an area of intense research, as evidenced by many recent publications. Historically, these processes have had notoriously low efficiencies, and many authorities reject the very notion that incineration should be considered as a viable recycling option, but recent research effort has been rewarded with significant advances, and shows that incineration with energy recovery, accompanied by CO₂ capture and usage, must be considered alongside pyrolysis or hydrothermal treatments [52]. The capture of CO₂ from flue gas has been problematic, but the development [53] of effective processes for the direct extraction of atmospheric CO₂ may mean this could soon not be an issue. These developments also raise the prospect of CO₂ → monomer → polymer being an effective means for achieving negative greenhouse emissions. There are other factors to consider. Depending on the composition of the plastic mix, there will typically also be an amount of non-combustible waste produced. The burning of plastics containing heteroatoms (atoms other than H, C, or O) will produce byproducts. These could include HCl from PVC, nitrogen oxides from nylon, and hydrogen cyanide from polyurethanes. Sorting plastics destined for recycling will always provide benefits.

The fourth route for chemical recycling involves controlled biodegradation [54,55]. Many polyesters, including PET, can be efficiently transformed into monomers by enzymic hydrolysis. The process has been used in the pilot-scale production of terephthalic acid from PET [56]. The current disadvantages of controlled biodegradation are a large footprint for the recycling facility and a relatively slow rate of enzymic hydrolysis. This, also, is an area where significant advances are being made (see also the section on plastics biodegradation below).

The various strategies for plastics recycling are summarized in Figure 3. They include: mechanical recycling; chemical recycling by depolymerization-to-monomer and repolymerization; chemical recycling by pyrolysis or hydrothermal processing to provide petroleum feedstock, followed by cracking/monomer synthesis and repolymerization; chemical recycling by incineration, with energy recovery to carbon dioxide and water, followed by either monomer synthesis and repolymerization; or to provide petroleum feedstock, followed by cracking/monomer synthesis and repolymerization. The efficiency of these processes is substantially enhanced by the use of sorted plastic as a precursor. The importance of sorting into plastic types diminishes as we go from mechanical recycling through the spectrum of chemical recycling processes in the order mentioned.

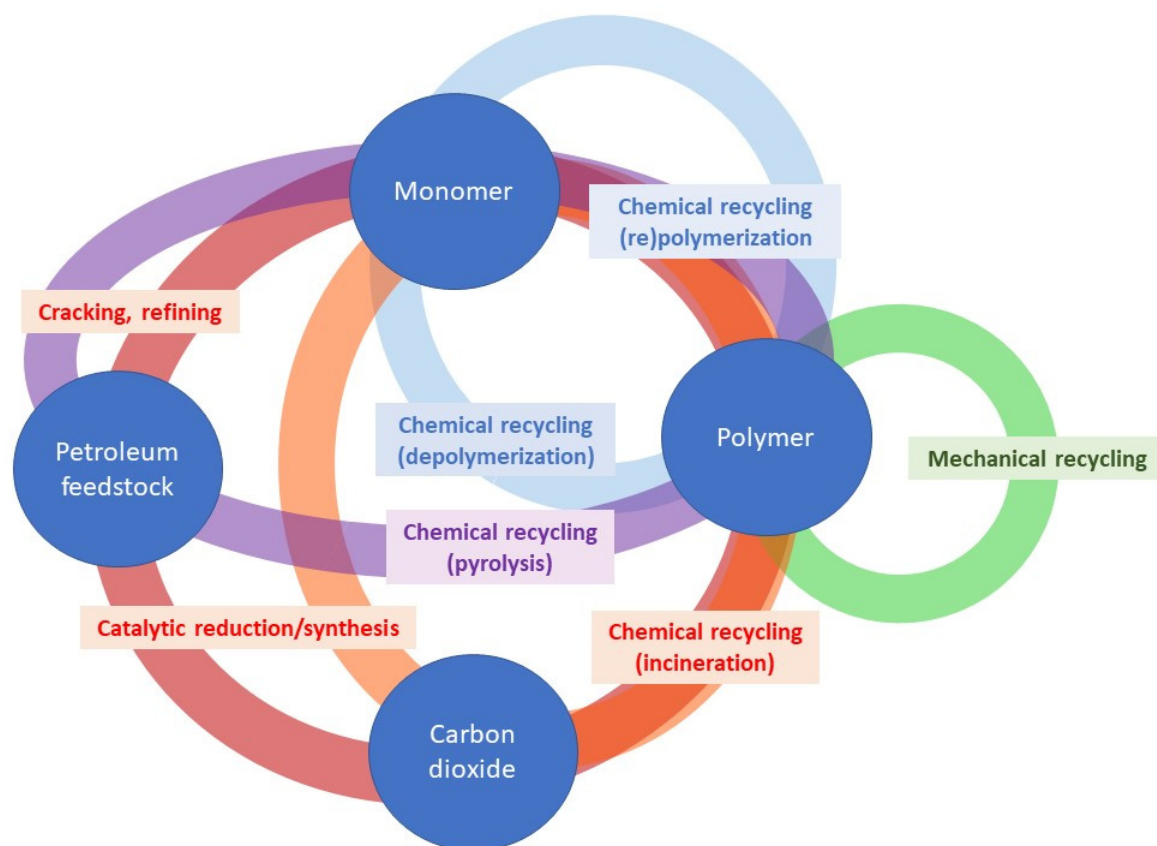


Figure 3. Plastic recycling strategies. Green cycle—mechanical recycling; blue cycle—depolymerization-to-monomer and repolymerization; violet cycle—pyrolysis or hydrothermal processing to petroleum feedstock—cracking/monomer synthesis—repolymerization; red cycle—incineration with energy recovery to carbon dioxide—monomer synthesis and repolymerization.

Biodegradation, composting and biotransformation are not directly mentioned in the cycles shown in Figure 3, but controlled biodegradation could provide a means of chemical recycling used for the conversion of plastics to monomers, or from plastics to petroleum feedstock as an alternative to pyrolysis or hydrothermal treatment, or from plastics to CO₂ (plus water and biomass) as an alternative to incineration (see below). The viability will depend on the type of plastic waste to be converted.

4. Microplastics and Nanoplastics

Some further terms should be defined. Microplastics are small particles of plastic with dimensions in the range of 0.1–100 µm. Nanoplastics are smaller particles that have dimensions in the range of 0.1–100 nm. However, definitions vary. In much of the literature, microplastics are considered to be plastic particles with dimensions less than about 5 mm,

while nanoplastics are those in the range of 1–1000 nm [57]. The analysis of environmental samples for microplastics and nanoplastics presents significant challenges [58–61].

There is a burgeoning literature on the formation of microplastics and nanoplastics from plastic waste, as well as on the impact of this on the aquatic or marine and soil or terrestrial environments and the potential effect on animal and, indeed, on human health (Figure 4) [62–67]. The fraction of papers that mention toxicity is significantly greater for nanoplastics than it is for microplastics.

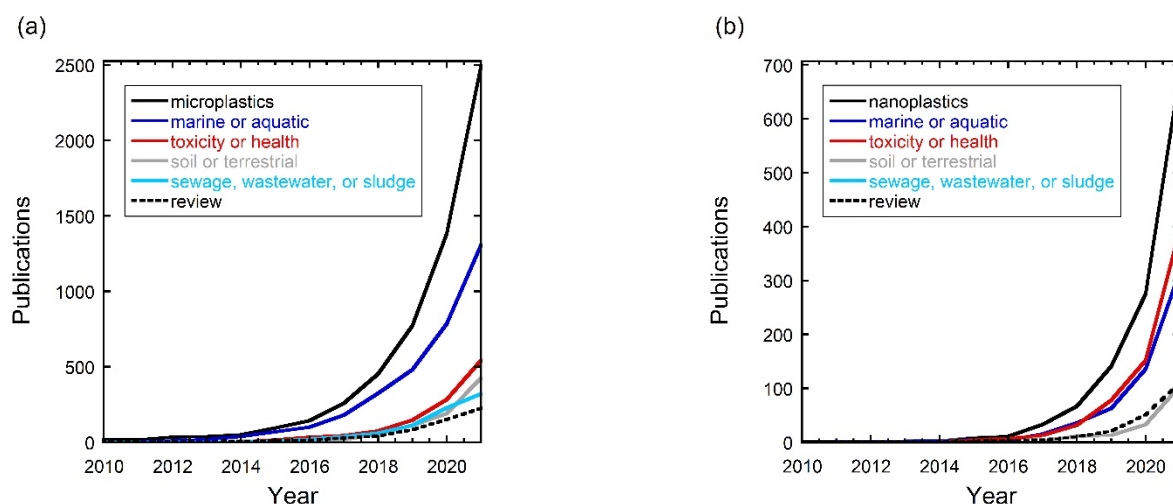


Figure 4. Publications on (a) microplastics, (b) nanoplastics and the fraction of those that include the keywords “marine” or “aquatic”, “toxicity” or “health”, “soil” or “terrestrial”, “sewage”, “wastewater” or “sludge”, or were a review of the field. Publications for 2021 are an estimate based on the number of publications that have appeared through April 2021 ($\times 3$). Based on a ScifinderTM search conducted on 15 May 2021. Approximately half of the papers on nanoplastics also include the term “microplastics”. The fractions relating to various topics are also not mutually exclusive.

Microplastics should typically not be present in well-formed plastic objects as made, whether from recycled or virgin plastic; rather, they are formed as a consequence of degradation. Microplastics have sometimes been purposely added as a mild abrasive in formulations for cosmetic applications. This use of microplastic beads is now banned in many countries. This document is then mainly concerned with microplastics formed by the degradation or weathering of plastics under the actions of light, oxidation and mechanical stress. It should be noted that microplastics not only come from the disintegration of plastic packaging but also potentially from surface erosion of paints or coatings, and from various objects made of plastic, which include garden furniture, railway sleepers, plastic roads, and the like. There is now also compelling evidence of microplastic production from objects formed from some virgin plastics, under conditions of normal usage [68].

The rate of formation of microplastics by degradation is strongly dependent on the type of plastic, on its molar mass and microstructure of the constituent polymer chains, on the surface and bulk morphology or the plastic coating or object, on the object’s history, and on the conditions/environments to which it has been subjected during processing, use, misuse and subsequent disposal.

Reviews suggest that the main sources of airborne, ocean, freshwater, and soil microplastics are, depending on location, the laundering of synthetic fabrics [69] and tire wear [70–74]. The leaching of microplastics from landfills, the bio-, photo- or mechanical disintegration of environmental macroplastic waste, and the wear of plastic and painted objects are also significant sources. Most research has concerned ocean microplastics [75–77]. Freshwater microplastics are a more recent, less-studied interest [78–80]. There is also significant interest in soil microplastics [63,67,81–83]. Both macroplastic and microplastic pollution derives from use in agriculture, for example as mulch and silage films [84].

5. Plastics Additives

With respect to developing whole-of-life strategies, it is important to also consider the other components, namely, the multitude of additives that may be present in plastics, whether petroleum-sourced or bio-based. The additives include heat stabilizers, flame retardants, antioxidants, dyes, pigments, surfactants, processing aids, plasticizers and fillers. We also need to consider the residual monomers, catalysts and byproducts from plastics manufacture. They can strongly influence the degradation and biodegradation of polymers, impede or even preclude some forms of recycling (in particular, mechanical recycling), and many can present significant issues in their own right [67,85,86]. A recent survey revealed >10,000 chemical compounds in this context [86]. Of these, >2400 were identified as substances of concern, in terms of their potential for persistence, bioaccumulation, or toxicity, in connection with current EU criteria.

Historical examples of problem additives that present a challenge to the environment include heavy-metal-based pigments (in coatings), phthalate plasticizers (in flexible PVC), and halogenated flame retardants (in polyolefins used for building and construction applications). These additive issues are typically thought of as a problem unique to petroleum-sourced plastics, but the issue can extend to bio-based plastics, which also comprise additives. In most cases, benign alternatives are available for problem additives, and for many, the most problematic, such as those mentioned, are not being used or are being phased out. Unfortunately, labeling on plastic products does not list plastics additives, and for historic landfill or environmental plastics, the worst has to be assumed.

6. Plastics Reuse

The last few years have yielded many examples of the reuse of mixed plastic waste. These include their use in plastic roads as an asphalt additive or replacement [87–89], and as wood alternatives, in garden furniture, fence posts, railway sleepers, and the like. Some research has been conducted into whether they meet the properties required for the intended applications. However, little is reported on degradation and weathering, or the potential for microplastic production, in the longer term. For example, tire wear is believed to be a major source of microplastics [70–74]. Plastic roads may mitigate tire wear. However, one can easily envisage that road wear may itself become a significant contributor to the microplastic problem [90].

The reuse of plastic must not be thought of as an end-point in a whole-of-life strategy. The fate of products made from reused plastics, and their recyclability, need themselves to be evaluated as part of the strategy. Reusing can be desirable, but it is not the same as recycling. While waste plastic reuse as described may well mitigate the rate of microplastic production, it must not be seen as a solution to the microplastics dilemma, and inappropriate reuse has the potential to make the problem more intractable. Various reuse strategies have merit, in removing macro-plastic waste from landfills, but there is no reason to believe that the potential for microplastic production is any less for these materials made of reconstituted plastic than it is for virgin plastics under similar conditions.

It is, thus, important to presort and select plastics for any intended reuse, not only for compatibility with the proposed application, but also for their longevity in the environment, the fate of the product of plastic reuse (i.e., its suitability for a second or subsequent reuse or recycling), and the potential for microplastic production and/or leaching of additives [19].

7. Plastics Biodegradation and Composting

This section relates to the biodegradation of plastics to CO₂, water and (hopefully benign) biomass, as distinct from the controlled biodegradation of polymers to monomers as mentioned above. There are many recent reviews that relate to the environmental biodegradation of plastics [91–94]. Biodegradable plastics and biodegradation have been seen by many to be an answer to the microplastics problem, and to the more general problem of plastic waste, and achieving a circular economy [56,92,95–98]. The term organic recycling has been defined as covering this process [99].

The terms “biodegradable” and “biodegradable plastics” are much misused. The IUPAC recommends the following term definitions [100]:

- bio-based polymer—composed of, or derived from, in whole or in part, biological products issued from the biomass (including plant, animal, and marine or forestry materials);
- biodegradable polymer—macromolecules or polymeric substances susceptible to degradation by biological activity by the lowering of the molar masses of the macromolecules that form the substances;
- biodegradation—degradation of a polymeric item due to cell-mediated phenomena;
- biodisintegration—disintegration resulting from the action of cells;
- biomacromolecule—a macromolecule (including proteins, nucleic acids, and polysaccharides) formed by living organisms;
- biopolymer—a substance composed of one type of biomacromolecule.

Note that the IUPAC has defined terms for polymers and not for the plastics that comprise them.

Some ostensibly biodegradable plastics may require many years and a specially constructed compost heap to fully biodegrade. The lifetime of petroleum-sourced plastics (i.e., HDPE, LDPE, LLDPE, PP, PVC, and PET) in the environment varies according to the type of plastic and the nature of the environment, but, when out of direct sunlight, and in the absence of mechanical stress, the rate of degradation is reported to average ca. 11 $\mu\text{m}/\text{year}$ and, for macroplastic objects, lifetimes may extend to hundreds of years [101]. In the absence of the appropriate biota, the lifetimes of bio-based plastics may not be very different. The lifetimes of microplastics and nanoplastics in the environment are less clear [102].

For biodegradation to be an effective method of removing plastics from the environment, biodegradable plastics must be sorted from non-biodegradable contaminants, or a process for treating the non-biodegradable residue has also to be devised and implemented. Bio-based polymers are not necessarily biodegradable on any reasonable time scale [103]. Bio-based polymers currently produced on an industrial scale include poly(lactic acid) (PLA), poly(butylene succinate) (PBS), poly(butylene adipate terephthalate) (PBAT), and polyhydroxyalkonates (PHAs) and various starch-based blends. So-called bio-PET and bio-PE “drop-ins” are also produced on an industrial scale. They are identical to, but more expensive to produce, than equivalent petrochemical-sourced plastics [104].

We therefore also provide the ASTM definition of compostable plastics [105]:

- compostable plastic—a plastic that undergoes degradation by biological processes during composting to yield CO_2 , water, inorganic compounds and biomass at a rate consistent with other compostable materials, and that leaves no visible, distinguishable, or toxic residue.

Some quite reasonably suggest that the term “biodegradable” be restricted to compostable plastics, and further, that the conditions and time scale of biodegradation should always be specified [106]. Biodegradable plastics should be distinguished from biodisintegratable plastics. These may be composed of a blend of conventional plastics with biodegradable plastics. In these cases, it is possible that, when composted, the biodegradable component degrades, while the non-biodegradable component is transformed to a microplastic form [67]. The presence of biodegradable plastics in mixed plastic waste may impair recycling opportunities for that waste. For example, it is important to separate PLA waste from PET waste in mechanical recycling.

There are other concerns that are sometimes raised with respect to composting and organic recycling. Ultimately, the amount of CO_2 that could potentially be produced by the biodegradation of a compostable plastic is the same as that released during incineration, and processes for CO_2 sequestration and usage are likely to be more difficult to implement [107]. To ensure compostability, the organic recycling of biodegradable polymers requires the use of biodegradable additives (e.g., flame retardants [108]). Moreover, plastics,

including biodegradable plastics, will often contain stabilizers, anti-oxidants, and anti-microbial agents to prolong their service life. These may significantly slow the composting process [109]. The composting of biodegradable plastics may also be a source of micro- and nanoparticles, either due to the presence of non-biodegradable components in the plastic or through the leaching of partially biodegraded plastic [110]. Biodisintegration is likely to be an intermediate stage in most biodegradation processes. These issues may be resolved by the certification of compostable plastics. The question is: can we keep certified compostable materials and non-certified compostable materials as separate waste streams?

8. Potential Solutions

The implementation of effective polymer recycling strategies can potentially alleviate the plastic/microplastic/nanoplastic problem going forward. However, major impediments are the cost and efficiency of plastic collection and sorting.

It is critically important to perform a life-cycle assessment for plastics. This needs to be carried out for individual plastics, even to the specific grade or composition. The requirement should apply to all plastics, whether fossil-fuel-derived, recycled, reused or bio-based. This should be performed by the plastic producer. However, in that the use is not always predictable, this may need to be redone or augmented each time the plastic is processed, transformed, recycled, or reused.

The issue of tracking plastics might be solved through the inclusion of taggants or molecular barcoding [14,111,112]. Various possibilities are being researched; none has been fully implemented. These might be introduced at the point of plastics manufacture, and with each processing or reprocessing step. It has been proposed that molecular barcodes might take the form of sequence-defined polymers that can be read by spectroscopic means [111]. This would facilitate the sorting effort, would mean that plastic objects could be traced to their point of origin, and that their compositions might be known, down to the level of minor additives. Impediments to this method are that taggants/tokens/barcodes would need to be both miscible and compatible with the containing plastics, not influence their properties, must survive plastics processing and usage, and survive yet be benign in use and in the environment. There are also many challenges associated with ensuring global uptake of the technology, once developed.

Setting a “plastic price” that incorporates the cost of plastic pollution into the price of fossil fuel-based plastics has been proposed [76,113]. This could be an extension of the product stewardship schemes that have been established or are being established in a number of jurisdictions.

One suggested method of implementation is a “voluntary contribution” paid by producers [76]. This might go some way toward making plastics recycling processes economically viable and incentivize the collection of plastic waste. While the proposal has merit, to be fully effective it has to be taken up globally, and the funds collected to be directed toward the problems in a transparent way. Organizations such as OECD and UNESCO have a role to play here.

Another possibility is that countries could go it alone and impose a levy on local producers, with a corresponding tariff on imported fossil fuel-based plastics and materials/objects produced from them. The latter may be particularly important in countries like Australia, where there is little local plastic production. This is more complicated, but is perhaps more readily achievable, free trade agreements notwithstanding.

A packaging deposit scheme might be implemented, whereby packaging companies pay a deposit, based on packages produced, that can be redeemed with the return of the package to a recycling center in a sorted recyclable state. This cost would of course be passed on to the consumer. The consumers in developed countries would likely tolerate this. The acceptance of having to pay for shopping bags at the supermarket attests to this. A very high deposit price would need to be applied to fishing nets and the like, one that is sufficient to justify recovery from the marine environment.

9. Conclusions

The need to develop and implement effective whole-of-life strategies for the use of plastic materials is widely recognized, as evidenced by the dramatic increase in the use of terms such as “circular economy” [20,77,114–118], “whole of life”, “life-cycle assessment” [27], and at least some interpretations of “sustainable plastics” [119] in the scientific literature. The problem with cycles is that we continue to circle and a clear direction remains elusive. An interpretation of the circular economy in the context of plastics is presented in Figures 5 and 6. For a circular economy, a whole-of-life strategy must only have an endpoint in rebirth.

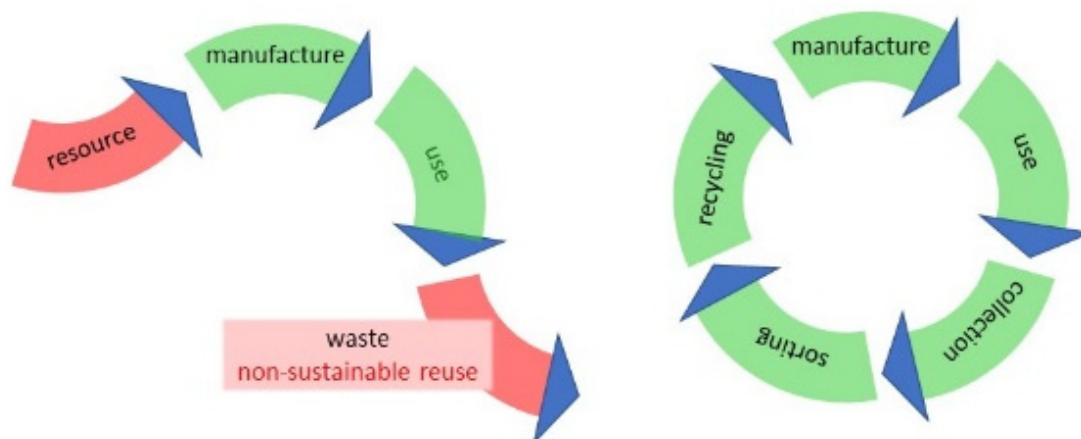


Figure 5. Idealized depictions of the linear and circular plastic economies. The circular economy requires no losses to the environment at any stage of the cycle. Non-sustainable reuse, for example, as an asphalt modifier in plastic roads, is better than waste, but is not a clear departure from the linear economy. For most plastics, current practice corresponds to a state of transition between the linear and the circular economies.

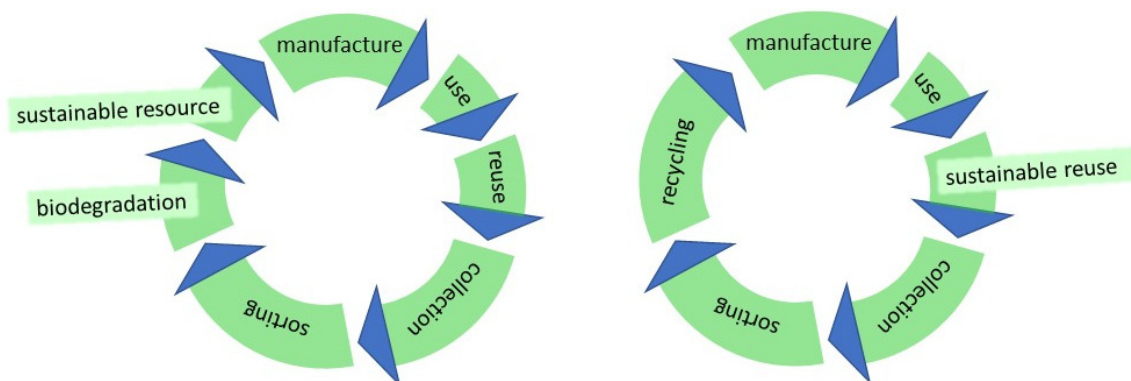


Figure 6. Idealized depictions of possible pathways for the inclusion of biodegradable plastics or plastic reuse into a circular economy. The circular economy requires no losses to the environment at any stage of the cycle. Further collection and sorting steps may interpose between use and reuse.

Unfortunately, the literature in this area is corrupted by half-truths, assumptions, over-generalizations, and outmoded data. The processes that fit the circular economy concept, and our definitions of what is green or sustainable, need to continually evolve to keep pace with scientific advances. It must be seen that science relates to probabilities that may change, not to immutable facts.

We have tended to downplay reuse as a viable solution to the plastic problem. Reuse is never an endpoint; rather, it is a new product, the lifecycle of which needs to be subject to critical assessment. Non-sustainable reuse (Figure 5) is not a departure from the linear

economy. The term “biodegradation” is used in many contexts. It can be a valid means of chemical recycling, taking plastics back to monomers for repolymerization. It can be a process by which to return bio-based polymers to CO₂, water and biomass. However, it can also lead to the biodisintegration of plastics into micro- and nanoplastics. The terms “biodegradation” and “biodegradable plastic” should not be used without qualification to explain what is meant. A depiction of biodegradation in the context of the circular economy is presented in Figure 6.

In this review, we have attempted to assess the potential for implementing whole-of-life strategies for plastics to achieve our vision of a circular economy. We do not provide full solutions. As a worldwide community, we have not come that far. Rather, we emphasize the need for research to establish the most effective recycling processes for different plastics. A universal solution is unlikely. The need for effective sorting techniques (or maybe not getting them mixed up in the first place) is needed, irrespective of the particular plastic or bioplastic. The implementation of effective means of tracking plastics, their composition (including additives) and history is extremely important in the context. Reuse processes need to be assessed regarding the sustainability and environmental impact of the reuse, ideally before the reuse takes place. The cost of sorting, cleaning and recycling, by whatever process, means that recycled plastics are often not able to compete with virgin plastic in the marketplace. The cost of plastics to the user needs to reflect the whole-of-life cost, rather than simply the cost of production.

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