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Review

Scientist's warning on recasting our relationship with plastics: Looking to the broader context

Christopher J. Rhodes[1,2,]*

[1] Fresh-lands Environmental Actions, Reading, Berkshire RG4 5BE, United Kingdom.
[2] School of Life Sciences, Pharmacy and Chemistry, Kingston University, Penrhyn Road, Kingston upon Thames, Surrey KT1 2EE, United Kingdom.

* **Correspondence:** Email: c.rhodes@kingston.ac.uk; cjrhodes@fresh-lands.com.

Abstract: In 2019, 460 Mt of plastics were manufactured, and this number is expected to nearly triple by 2060. Globally, plastic waste amounts to more than 400 Mt/a, roughly half being from single-use plastics (e.g., packaging), and is projected to rise to above 1,000 Mt by 2060. By 2050, 20% of the world's oil supply will be consumed by plastics, along with 15% of the global carbon budget. Microplastics (MPs) cannot be avoided entirely, as long as plastic materials remain in use, as they form through the wear and tear of plastic items and plastic-coated surfaces, including vehicle components (tires, brakes, upholstery, etc.), road markings, marine coatings, clothing, paints, agricultural films, and synthetic textiles. Plastic pollution poses serious health risks, impairs biodiversity, and contributes to emissions/climate change along the entire "cradle-to-grave" chain. Consequent damages to ecosystems impair their ability to absorb carbon, such as in phytoplankton and soils. Toxic substances associated with plastics and their uses further threaten health. Globally, only about 9% of plastic waste is recycled, varying from region to region. Better interception and collection of plastic items and post-use management are critical to keep them away from the environment. The end-of-life aspect should be designed into a plastic item before its production. Contaminant materials that challenge recycling should be avoided. Plastic waste must be reduced, mainly by using fewer plastic items in the first place, and applying the Refuse, Reduce, Reuse, Repurpose, and Recycle (as a last resort) approach. Unnecessary and single/short-term-use plastics, especially disposable packaging, must be minimized. Plastics should be "saved" for critical applications, where there is no appropriate substitute, e.g., in healthcare, food/water provision, and electronics. This approach also agrees with the need to respect overall resource limits and planetary boundaries. Behavioral changes regarding consumption patterns are also necessary to bring humankind to below ecological overshoot and begin healing the current polycrisis.

Keywords: Plastic waste, recycling, microplastics, climate change, agriculture, biodiversity loss, behavioral change, polycrisis, planetary boundaries, ecological overshoot

1. Introduction

Plastics are wonder materials that have enabled the creation of the modern, industrialized world. They are now manufactured on a massive scale, but often for single-use applications, which feed our throwaway culture. As a consequence, plastic waste is now a growing problem, in part due to the robustness of plastics, meaning that they degrade slowly in the environment and tend to break down into increasingly smaller particles, namely microplastics (MPs) and nanoplastics (NPs). These threaten the health of ecosystems and organisms that inhabit them, including humans. Toxic chemicals associated with plastics and their uses pose further adverse health effects.

In this review, a systemic perspective is provided, surveying the plastics problem across the entire production–consumption–post-use chain, its impacts on climate and biodiversity, and the toxicity issues of MPs/NPs, considering recycling, biopolymers, agriculture and food production, circular economy, and the need for behavioral changes, to deal not only with plastics per se but the relationship between human society, the Earth's resources, and the need to respect planetary boundaries, by attenuating our overall consumption to below ecological overshoot.

This is not primarily a "chemistry" focused survey, of which there are many and various excellent examples, but an attempt to indicate where we might go as a human society. This is achieved by integrating all of the above and the need to build resilience against subsequent supply chain failures, in part through relocalizing many of our activities, including growing food locally. To the best of our knowledge, there are few published reviews that offer a similar systems-level approach; we hope that this will stimulate actions to begin healing the current global polycrisis. The article will also be included in the Scientists' Warning collection of papers, which aims to highlight specific drivers of this predicament and possible solutions.

Polymers have been entwined in human culture for centuries, beginning around 1600 BC, when the ancient Mesoamericans began to process natural rubber into figurines, balls, and bands [1]. As human civilization advanced further, an increasing reliance on plastics and rubber was part of its journey, from initial endeavors with natural polymers (horn, waxes, natural rubber, and resins), to the development of modern thermoplastics, which began in the nineteenth century [2]. In 1839, vulcanized rubber was discovered serendipitously by Goodyear [3], and in that same year, Johann Simon produced polystyrene (PS), also by chance, from storax, a resin of the Turkish sweetgum tree *Liquidambar orientalis* [4].

The first truly synthetic plastic is generally considered to be Parkesine, made in 1856 in the UK by Alexander Parkes, who treated cellulose with nitric acid and found that the resulting material (cellulose nitrate, nitrocellulose, or pyroxylin [5]) was soluble in a range of organic solvents. When the solvent was evaporated, a transparent solid material appeared, which became moldable on heating (thermoplastic), thus creating a form of "synthetic ivory" [6,7]. Although billiard balls could indeed be made from this material, they would sometimes explode when struck. Nonetheless, demand for natural ivory was accordingly reduced, and it was reported that John Wesley Hyatt, who introduced it for this purpose, remarked that, "in spite of their tendency to catch fire, cellulose nitrate saved the elephant" [6]. In 1869, Hyatt produced "Celluloid" by plasticizing cellulose nitrate with camphor, thus enabling it to be processed into a photographic film [7]. Celluloids were used extensively for photographic and cinematographic purposes, and in 1889, Eastman marketed the first motion picture film on nitrate base [7]. "Safety film" came later, made from cellulose diacetate, although it was initially more expensive to produce, with a lower risk of fire but still prone to chemical hydrolysis and decomposition—the "vinegar syndrome", which is a serious problem for cinematic archives. Cellulose triacetate was introduced in the late 1940s, and acetate films were later replaced by polyester bases [8].

The events of two world wars led to many and various innovations, including the efficient, large-scale production of different types of plastic [7]. As commodity plastics, such as polyethylene terephthalate (PET), polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC), became widely available (accounting for 90% of all plastics sold [9]), a huge range of consumer products could be made, the numbers and varieties of which have expanded from the 1950s through to the present day. Since the Second World War, over 8.3 billion tons of plastic have been manufactured, following an exponential growth in annual production, from less than 2 Mt in 1950 to 460 Mt in 2019, a quantity that is expected to triple by 2060. More than half of all the plastics ever made have been produced since 2002 [10].

2. Plastics and the consumer society

The proliferation [7] of plastic materials in society is a consequence of their ease of production and cheapness, along with durability and strength, but low mass, as compared to other materials (e.g., metals). Thus, road transportation vehicles may be made from up to 20%, by weight, of plastic materials [2]. For the Boeing 787 "Dreamliner" Jumbo Jet, the proportion is around 50%, which gives 20% savings on the fuel needed to be burned for each flight, in comparison with a similar-sized aircraft made from traditional materials, such as aluminum [2]. The use of plastics in packaging and for medical applications has resulted in improved healthcare and food safety, while savings in energy, costs, and materials are a further advantage of using these materials, for example, in place of glass or metals. Thus, the use of PET drink bottles, rather than those made from glass or metal, is estimated to reduce energy consumption by 52% (83.2 GJ yr^{-1} in Europe alone), while curbing greenhouse gas emissions by 55% (4.3 million tons CO_2 eq yr^{-1} in Europe) [2]. The availability of cheap plastic has unleashed a flood of consumer goods across the world, overcoming many of the material limits and supply constraints of their natural equivalents, and placing otherwise expensive items into the hands of citizens ranging across the socioeconomic spectrum. In the early twentieth century, the introduction of widespread electrification resulted in a dramatic growth in demand for shellac (produced by the female lac beetle), which is a highly effective electrical insulator. However, to make one pound of shellac, the efforts of 15,000 beetles over 6 months were required. The invention of Bakelite [7], in 1907, by Leo Baekeland, provided an ideal substitute for shellac that could be heat-molded into numerous other consumer products; of particular importance being radio sets (thus made available in most households), furniture, and other objects, including telephones, vehicle parts, washing machines, toothbrushes, combs, cutlery, drinking vessels, and ashtrays, to list just a few. In 1938, Nylon was first used to make bristles for toothbrushes, being featured at the 1939 World's Fair [7]. Nylon became an iconic feature of the 1940s period, in the form of "nylons", as substitutes for the more expensive silk stockings [6].

Plastics have revolutionized almost all aspects of modern life, among which we may note clothing, healthcare, transportation, food preservation, and construction. In the medical industry, sterile packaging, disposable syringes, heart valves, catheters, blood bags, IV tubes, and other vital medical devices all depend on plastics, rendering them both easy to make and with reduced risks of contamination [11]. It has also been suggested that the vast proliferation of mobile phones and related devices might not have occurred if they had to be made of something else, such as metals [7]. Famously, in 1955, Life magazine published an article [12] on "Throwaway Living" that featured a picture of a family throwing a range of kitchen and other household items into the air, noting "The objects flying through the air in this picture would take 40 hours to clean—except that no housewife need bother. They are all meant to be thrown away after use" [12]. This is often cited as the dawn of what is now referred to, mainly dismissively, as the "throw-away society". Given that the presence of plastic items, objects, and devices is ubiquitous in the modern age, plastic has been proposed as a distinctive stratal component and a possible critical geological indicator of the Anthropocene [13].

3. Plastic production, waste, and international governance

In 2019, 460 Mt of plastics were produced, and this number is projected to reach 1,230 Mt by 2060 [10]. Similarly, plastic waste currently amounts to more than 400 Mt/a, but by 2060, it is expected to exceed 1,000 Mt/a [14]. It has been estimated that, by 2050, there will be more plastic waste (by mass) than fish in the sea [15]. Two-thirds of all plastics are used for short-life applications, with the vast majority of plastic food and beverage packaging being for single use [16]. Plastic packaging accounts for 36% of all plastics made, but amounts to 47% of all plastic waste; 90% of all plastic items are used once and then discarded, which corresponds to around 50% of the total mass of plastics manufactured [17]. The result is that more than 200 Mt of single-use plastic waste is created every year [18]. The discharge of plastic waste, particularly into the oceans, is now universally regarded as an overwhelming global problem, as profoundly demonstrated in the final episode of the Blue Planet II series [19] on BBC television, narrated by Sir David Attenborough, and giving rise to "The Blue Planet Effect": an energizing of actions across the world to limit unnecessary use of plastic and reduce plastic waste. "Plasticus", a "whale", made from a quarter of a ton of waste plastic (the amount estimated to enter the oceans every second), was used in The Sky Ocean Rescue Campaign [20]. Plastic is also mentioned in Pope Francis' encyclical, Laudato Si [21], on "On Care for our Common Home", but in broader reference to the moral imperative for humans to curb excessive consumerism, thus levelling down our current hyperconsumption of fossil fuels and all other resources, and consequent impacts upon the Earth. Given its broad, societal significance, the encyclical was covered in an Editorial by the Nature journal [22].

International governance of plastics is currently centered on the UN Global Plastics Treaty, a legally binding instrument being negotiated by 175 nations via an Intergovernmental Negotiating Committee (INC) to address the full lifecycle of plastic pollution, from production to disposal, aiming to create a circular economy and end pollution by 2040, though facing challenges from petrochemical interests and geopolitical divides. The INC has held several sessions (INC-1 to INC-5.2) since late 2022, with the next one (INC-5.3) scheduled for February 2026, working toward a final treaty. The treaty aims to cover the entire plastic value chain, including production, design, chemicals, and waste management, moving beyond voluntary actions to legally binding regulations, and a draft report has been submitted from the resumed fifth session of the UN Intergovernmental Negotiating Committee for Plastics (INC 5.2) [23]. The "Lancet Countdown on Health and Plastics" report has been issued to inform the Global Plastics Treaty, which emphasizes the enormous harm caused by the entire production-to-disposal life chain of plastics to humans and the wider environment, in terms of health, social, and economic costs. As stated, "coincident with the expected finalization of this treaty... the Countdown will identify, track, and regularly report on a suite of geographically and temporally representative indicators that monitor progress toward reducing plastic exposures and mitigating plastics' harms to human and planetary health" [24].

In analogy with Earth Overshoot Day, Plastic Overshoot Day has been introduced, and in 2025, this fell on September 5th [25]. It has been shown that the ratio of primary waste/production varies from sector to sector [17] and increases as its lifetime in the particular sector application decreases. Thus, it is 20% for building and construction, 33% for industrial machinery, 63% for transportation, 88% for consumer and institutional products, and 97% for packaging, hence the high share of plastic waste accounted for by the latter [17]. A highly informative review of the global situation regarding plastic waste has been presented, which includes aspects of process-oriented practices for plastic and plastic waste management, and also considers, more broadly, legal frameworks and policies for sustainable environmental management [26]. Wei et al. proposed that climate change and plastic pollution are interconnected, since, as temperatures and moisture levels increase, particular characteristics of plastic materials are changed, leading to enhanced levels of waste, the generation of microplastics, and the discharge of toxic substances into the environment [27].

4. Microplastics

Song et al. [28] have addressed issues of defining microplastics and noted that, since the following definition directly categorizes the sources of MPs into two types (i.e., primary and secondary), it has become widely accepted: "[a microplastic is] any synthetic solid particle or polymeric matrix, with regular or irregular shape and with size ranging from 1 μm to 5 mm, of either primary or secondary manufacturing origin, which are insoluble in water".

Primary microplastics (MPs) are those originally manufactured at the sizes in which they are found in the environment, for example, microbeads, and nurdles from which plastic items are made. Secondary microplastics are formed by the degradation of larger plastic items, including bottles to hold water and other drinks, plastic bags, and fishing nets. There is, nonetheless, some controversy over whether certain MPs should be considered primary or secondary; for example, particles from the wear of vehicle tires on road surfaces and microfibers from washing textiles. However, Song et al. [28]

proposed that this can be resolved by using the classifications “intentional” and “unintentional”, so that primary MPs are those actually manufactured at <5 mm dimensions, while all others can be categorized as “secondary”, having broken down from larger objects or painted areas, including road markings, ships, and bridges.

MPs have been found wherever they have been sought [17], e.g., in the air, rivers, aquifers, mountains, glaciers, soils, Arctic sea ice, insects, drinking water, food (honey, sugar, salt, beer, seafood), the oceans and ocean sediments, including waters and deep sea sediments around Antarctica, and in the depths of the oceans [17]. Atmospheric transport has been identified as a major transfer route for MPs to remote regions, for example, the Arctic [29]. Evidence has been presented [30] that MPs can be transferred through different life stages of mosquitoes that use different habitats and can thus be potentially transferred from aquatic systems by flying insects and those that feed on them, spreading them even further [30].

It has been estimated that, in 2019, there were 82–358 trillion plastic particles, primarily MPs, floating in the world’s oceans, with a total mass of 1.1–4.9 million tons, and that a rapid increase had occurred since 2005 [31]. Although microbeads are now banned in many countries, e.g., as used in cosmetics and as abrasives for industrial surface cleaning applications, MPs cannot be altogether avoided, so long as plastic materials remain in use, since they are created through wear and tear, e.g., from the fragmentation and abrasion of vehicle components (tires, brakes, upholstery, etc.), road markings, painted surfaces, marine coatings, city dust, clothing, upholstery, paints, agricultural films, and synthetic textiles [7,17]. It has been estimated that approximately 3 million tons (Mt) per year of MPs are released into the environment, almost half (1.41 Mt) from tire abrasion, 660,000 tons from city dust, 600,000 tons from road markings, 240,000 tons from washing textiles, and 60,000 tons from marine coatings. China is the greatest emitter of global MPs (20%), followed by North America (16%), Asia (14%), and Western Europe (11%) [32].

Exposure of plastic items to the erosive forces of the outdoor environment, e.g., polytunnels, agricultural films (mulches), construction materials, and vehicles, also generates secondary MPs [33,34]. The most effective long-term solution to the microplastic (MP) problem is to reduce overall plastic consumption, since MPs, once formed, are difficult to remove from the environment [35].

Although definitions vary, nanoplastics (NP) may be characterized by either a critical dimension of less than 1 μm (i.e., 1000 nm) or less than 100 nm [36,37]. NPs are either considered to be short-lived entities resulting from the fragmentation of MPs, or that their concentrations are actually high and constitute a significant environmental threat; this ambiguity is the result of difficulties in detecting them [38]. However, NPs have been confirmed to exist in the North Atlantic Subtropical Gyre [39] and, by means of a TD-PTR-MS method, it has been determined that some 27 million tons of NPs exist in the top 10 m of water in the North Atlantic; previous estimates pointed to this amount for the entire Atlantic Ocean [40]. Further promise in the determination of the amount of NPs present in the environment has been shown by methods such as Raman spectroscopy combined with optical tweezers [41], nano-Fourier-transform infrared, or atomic-force infrared spectroscopy. Rapid, cheap, and sensitive determinations of NPs may be possible using fluorescence-based methods [42], although, due to the complexity of the problem, nanoscale properties and the interaction of NPs with biological molecules must be addressed at both high spatial and temporal resolutions, and at the most fundamental level [43].

Due to their small size, NPs can penetrate the tissues and organs of living creatures, potentially resulting in harmful biological effects [44]. NPs can be formed by the mechanical breakdown of commonly used polystyrene products, such as coffee cup lids and expanded PS foam [45]. Toxicity, varying with particle size, has been demonstrated in zooplankton [45], along with size-dependent uptake in these and other aquatic organisms. NPs have been shown to traverse food webs, ranging from algae, zooplankton, and planktivorous fish to piscivorous fish [45], potentially causing changes in the behavior and metabolism of the fish along this feeding chain [45]. It is extremely difficult to confirm the presence of NPs in biological samples [39] due to their small size and chemical similarity to other organic matter present.

It has been shown [46] that spherical MPs may pass through an organism and be excreted unchanged; if they are sufficiently small, translocation can occur, for example, across the intestinal epithelium. However, when Antarctic krill (*Euphausia superba*) were exposed to 31.5 µm MPs, these were converted into NPs of <1 µm size, small enough to cross physical and physiological barriers. It is speculated that Antarctic krill, and possibly other species too, may be critical agents in the biogeochemical cycling and fate of plastics [46].

5. Environmental and human health impacts of plastic pollution

Millions of sea animals and birds are killed each year by entanglement or ingestion [47] involving larger plastic waste items. Overall effects of MP/NPs on ecosystems and food chains are likely to be detrimental, including their effects on soil organisms, as illustrated later on in this section. Plastic items have been found in the stomachs of seabirds, sea turtles, seals, whales, and fish [48]; MPs have been identified in the tissues and organs of a range of marine creatures [45,49]. Coral reefs provide habitat for more than one quarter of marine life [50], and yet, alarmingly, 89% of 125,000 corals across the Asia-Pacific region, fouled by plastic, showed signs of disease, in contrast with their plastic-free counterparts, all but 4% of which appeared healthy. Plastic is harmful to corals as a consequence of light deprivation, the release of toxins, and anoxia, which encourages pathogen invasion [51]. It has been reported that the leachates from plastic items, such as HDPE bags and PVC matting, can impair growth and oxygen production from *Prochlorococcus*, which is the most abundant photosynthetic bacterium in the ocean [52].

In contrast with the majority of studies, which sample MPs from within the upper half meter of the oceans, a depth-profiling study was conducted to investigate the distribution and potential transport mechanisms of subsurface (below about 50-cm depth) MPs throughout the oceanic water column, giving a range of abundances from 10^{-4} to 10^{4} particles per cubic meter [53]. The fact that these particles may occupy the entire water column is highly significant, since in marine environments, MP/NPs pose a direct danger to plankton and other key Earth ecosystems [54], including mangroves and coral reefs [55]. Since MPs may further serve as vectors of major ocean pollutants, an additional hazard to marine ecosystems (and humans) is presented [56]. Bisphenol-A (PBA), plasticizers, and other related materials have been identified in the bodies of humans and other animals, which may act, inter alia, as endocrine disruptors [17]. Possible human health effects of MP/NPs were identified in a review by Yee et al., including their potential to induce inflammation, oxidative stress, apoptosis, and metabolic homeostasis (leading to obesity) [57].

The primary ecotoxicological mechanisms of plastics, at both cellular and molecular levels, involve oxidative stress, inflammatory processes, physical damage, and the leaching of toxic chemical additives. These responses tend to depend on the size of the plastic (e.g., MPs vs NPs), its concentration, and the particular type of organism being affected by it. After permeating into the stratum corneum, MPs and NPs can enter an organism and interact with numerous target cells. Size, surface chemistry, or charge of the biological elements encountered by the particles, including proteins, phospholipids, and carbohydrates, all influence such interactions. NPs can create "protein coronas" (coatings) around themselves, and so, when they interact with organs or skin cells, it is not as fully exposed (nano)particles, which may increase the rate of translocation of the NPs [57]. Despite the common perception of bioplastics as being "environmentally friendly", it has been shown that endocrine disruptors leach from commercial bioplastics and that NPs derived from bioplastics induce oxidative stress via "conserved pathways" to a greater degree than MPs. NP bioaccumulation in marine bivalves, as a result of polyester photodegradation, has been demonstrated from field studies. It has also been stressed that current certifications do not sufficiently regulate toxic intermediates that stem from non-fully degradable biosourced plastics [58].

The literature regarding MPs as a significant threat to environmental and food safety has been surveyed, from which it is proposed that the widespread use of face masks (which contain polypropylene) in dealing with COVID-19, combined with poor waste management, may have caused an increase in MP pollution. The long-term consequences could be devastating, should urgent action not be taken [59]. A systematic evidence map has been compiled of MP/NPs present in foodstuffs in contact with different kinds of plastic food contact agents (FCAs). It was concluded that MP/NPs can migrate throughout the food system, as a result of normal/intended use of plastic items, and that better testing and regulation are needed to mitigate this [60]. Although a conclusive demonstration of an actual illness being caused by MP/NPs in humans is so far lacking, more indirect indications are accumulating. Thus, it has been shown that concentrations of MPs are higher in the placentas of premature births [61]. Nihart et al. reported the bioaccumulation of shard-like, nanoscale fragments in decedent human brains, the concentration of which had increased progressively in samples taken from 2007 to 2025. Furthermore, an even greater accumulation of MP/NPs was observed in a cohort of decedent brains with documented dementia diagnosis, with notable deposition in cerebrovascular walls and immune cells [62]. Non-communicable diseases, such as cardiovascular disease, cancer, COPD, and asthma, might be exacerbated by the inflammatory action of MP/NPs, thus increasing the global burden of such ailments [63]. In order to obtain a definitive view of human health and other consequences of environmental plastics, the Minderoo-Monaco Commission on Plastics and Human Health has been established [10], stating as its intentions "to comprehensively examine plastics' impacts across their life cycle on: (1) human health and well-being; (2) the global environment, especially the ocean; (3) the economy; and (4) vulnerable populations-the poor, minorities, and the world's children. On the basis of this examination, the Commission offers science-based recommendations designed to support development of a Global Plastics Treaty, protect human health, and save lives" [10].

In a detailed study from The Lancet, it has been emphasized that we are in the midst of a "plastics crisis", as this is a "grave, growing and under-recognized danger" to people and the planet, causing "disease and death" from infancy to old age. The authors note that plastics damage human health through a matrix of influences, including direct exposure to landfills or chemical plant emissions, environmental contamination, absorption through food packaging, microplastics, air and soil pollution, and the burning of related fossil fuel feedstocks. The health consequences range from birth defects and microplastic poisoning in the womb to asthma, cancers of various kinds, heart attacks, hormone disruption, and developmental problems [24]. Massive hidden economic costs are borne by governments and societies, which fall disproportionately upon low-income and at-risk populations. Toxic substances associated with plastics and their uses further enlarge their health impacts. The economic costs of bisphenol A (BPA), phthalates (such as DEHP), and polybrominated diphenyl ethers (PBDEs) are estimated at $1.5 trillion across 38 countries, which represent one-third of the world's population. Approximately 4200 chemical substances associated with plastics have been found to be hazardous due to their toxic effects, persistence, and bioaccumulation. Almost 1500 are carcinogenic, mutagenic, or toxic to reproduction, and more than 1700 are toxic to specific organs such as the liver [24].

From a comprehensive review of the literature, it is concluded that MPs can affect the transport, fate, transformation, and bioavailability of contaminants in soil ecosystems and further threaten food security and human health. Furthermore, the structure, diversity, and functions of soil microbes are all affected by MPs at high concentrations, while plastic debris can be ingested by soil fauna, with consequent detrimental effects [64]. In one study, when sewage sludge was applied to soil over a period of 5 years, the soil MP levels were found to increase by 1450%; hence, MPs should be considered along with other types of pollution (such as heavy metals) that can be transferred to soils [65]. Adverse effects of MPs on the physicochemical properties of soils and, accordingly, the health of crops, in agricultural systems have been demonstrated [33]. Furthermore, MPs are shown to be directly toxic to earthworms, which are keystone species and ecosystem engineers in soils [66].

Since plants can uptake MPs, concerns have been raised about the consequent health risks of their transmission across the food chain [64]. MPs can enter plants via both their leaves and roots [67]. The detection, mechanisms, and factors that may influence uptake of MPs by plants have been discussed elsewhere [68].

6. Plastics as drivers of climate change and biodiversity loss

Plastic manufacturing is energy-intensive, and its contribution to climate change is such that plastics have been described as being "The New Coal" [69]. The Ellen MacArthur Foundation's "New Plastics Economy" report [15] estimated that, in 2014, the plastics industry consumed 6% of the global oil supply [including natural gas liquids (NGL)] and this was projected to reach 20% by 2050.

The United Nations Environment Programme made two estimates for carbon emission contributions from plastic: (1) 2.1 Gt CO_2 by 2040, consuming 19% of the carbon budget (for a 2 °C scenario), and (2) 6.5 Gt CO_2 in 2050, consuming 15% of the carbon budget, under current trends [70]. A "15% of the carbon budget by 2050" figure was also obtained by the Ellen MacArthur Foundation [15]. A comprehensive report has been published by the Centre for International and Environmental Law, "Plastic and Climate—the hidden costs of a plastic planet", which concludes that, "at current levels (BAU), greenhouse gas emissions from the plastic lifecycle threaten the ability of the global community to keep global temperature rise below 1.5 °C. By 2050, the [cumulative] greenhouse gas emissions from plastic could reach over 56 gigatons—10%–13% of the entire remaining carbon budget" [71]. Thus, these separate studies are in fair accord as to what might be expected if we continue on the present course.

The degradation of MPs in the aquatic environment is another potential source of greenhouse gases (CH_4 plus CO_2), along with other harmful substances [72]. It has also been shown that commonly used plastics (e.g., polyethylene) are significant sources of methane and ethylene under ambient solar irradiation, especially in aqueous environments [73]. The carbon cycling of the oceans is adversely affected by MPs, which have been found to reduce the photosynthesis rate of phytoplankton by up to 45% [74]. MPs can also restrict the growth of zooplankton, which are important in being the primary consumers of phytoplankton, and which therefore aid the transfer of fixed carbon from phytoplankton to the deep ocean. This carbon transfer process is further impeded by the MPs adding buoyancy to the zooplankton feces, which sink more slowly [75].

Highlighting yet another potential climate change driver, it has been discovered that the atmospheric transport of MPs to remote regions is highly efficient, and that the Arctic may be a particularly effective sink for them, where the light-absorbing properties of particles from tire-wear and brake-wear may cause accelerated warming and melting of the cryosphere [76]. The toxic effects of plastics at each stage of their lifecycle—extraction of fossil fuels, production, manufacturing, use, recycling, and disposal—on biodiversity and wildlife were the subject of a report by the Geneva Environment Network [77]. The integrated nature of the effects of plastic pollution has also been explored, leading to the conclusion that, as a result of their polluting the environment, plastics both impact climate change and accelerate biodiversity loss, hence aggravating the "Triple Planetary Crisis" (biodiversity loss, climate change, pollution) [78].

Looking further to the broader picture, it has been shown that plastic pollution exacerbates the consequences of breaching all other planetary boundaries [79]. Thus, evidence has been presented that plastics have exceeded their planetary safe operating space; moreover, they influence multiple Earth system processes as a result of the extraction of resources, production, and emissions, and on to their final environmental fate and impacts (an "impact chain"). Consequently, it is concluded that it would be detrimental to try and establish a *single* planetary boundary for plastics. Instead, it is proposed that, in order to measure, monitor, and mitigate global plastics pollution, appropriate, biophysically defined control variables should be established for the planetary boundaries framework. The authors "call for urgent action, recognizing plastics pollution not only as a waste management problem but as an integrative part of climate change, biodiversity, and natural-resource-use policy" [79]. The seriousness of this situation may be augmented by the fact that the seventh (out of nine) planetary boundary, ocean acidification, is now close to being, or is already, transgressed [80]. Given the demonstrated contribution of plastics to enhanced greenhouse gas emissions and their negative effect on oceanic zooplankton and phytoplankton (carbon cycling), it seems probable that plastic pollution can only further worsen the outcomes of breaching this boundary, too. The United Nations has proposed that a new plastics economy should be introduced in order to protect the climate [81]. In this same vein, Bauer et al. have shown how "carbon lock-ins" are stubbornly entrenched across the value chain (production, use, and recycling) for plastics, which can only be overcome by a combination of demand reduction, the use of bio-based feedstocks, and circular economy principles, which must be combined with strict governance and enforceable regulation [82].

7. Plastics recycling

In 2019, 352 Mt of plastic waste was produced, which was projected to increase to around 409 Mt in 2025 [83]. Although the concept of recycling arose in the early days of petroleum plastics, only about 9% of global plastic waste is currently recycled. The rate of plastic waste recycling varies from region to region [84], but has been assessed (2019) at 12%, 13% and 4% in Europe, China, and the US, respectively [85].

The recovery of plastic waste is mainly carried out using mechanical means, using washing to liberate the organic component, which is shredded, melted, and remolded. Virgin plastic of the same type is generally added to the mix, enabling new plastic items to be fabricated, of similar quality to the original ones. However, PET and PE are the only plastics significantly recovered, thus accounting for 9% and 37%, respectively, of all plastics manufactured, with little more than 1% of the remainder being recovered [17].

Various methods of chemical recycling employ waste plastic materials as feedstocks, which are converted to gases, waxes, or fuels. However, the energy costs and other factors are sufficiently high that they are currently not used extensively [17]. Another possible option for the effective utilization of plastic waste is to make non-polymer, high-value products, e.g., conversion of PET to paracetamol using genetically engineered bacteria [86].

An ideal strategy would be to deconstruct a polymer back to its initial monomers, and so produce fresh virgin plastic by repolymerizing them [87]. To this end, Zhu et al. have developed a plastic from a suitably functionalized γ-butyrolactone monomer, which could be produced at ambient temperature and under mild conditions. The material had good thermal properties and could also be recycled back to its monomer by thermolysis or chemolysis. Thus, the prospect of infinite recycling (allowing for some degree of material loss at each cycling stage) is offered [88]. Although this is not currently viable, on the grounds of cost and energy inputs, the strategy offers promise for the future, e.g., as part of a New Plastics Economy [15]. However, even if such materials do become viable for practical applications, they are only fully useful if effective plastic waste collection is in place first.

Means are also being sought to deal with mixtures of plastics [7,87] to obviate laborious mechanical recovery, which also results in the molecular deterioration of the material, meaning that the final product is correspondingly less desirable than the virgin product [87]. Colorants, plasticizers, and fire retardants, among other additives, may also be problematic, in regard to recycling, leading to lower value products [89] ("downcycling"); however, chemical recycling methods for converting ("upcycling") plastic waste into high value products, could be game changers, and hence are the goals of active research [7,87,89]. Recycled plastics may also be employed in applications to create electronic devices, such as sensors and supercapacitors [90-92].

An OECD report examined why only 9% of manufactured plastic is actually recycled [93], a point that is stressed elsewhere and framed in the context of a circular economy [94]. Prospects for depolymerization within a circular plastics system have also been surveyed, including novel polymers that might be introduced for this purpose [95].

Contamination with food and labels, and the diversity and complexity of additives in some plastics, provide barriers to their being recycled. Another impedance is purely economic, since it is often cheaper to make new ("virgin") plastic than it is to recycle it; accordingly, investment in recycling infrastructure and technology is not encouraged, thus maintaining the pattern of low recycling rates [96]. Thus, as an essential means to encourage greater recycling of plastic waste, it is necessary to increase its value, as compared with virgin materials [97,98]. Enhanced valorization of plastic waste has also been proposed as one way to reduce the proliferation of these materials in low-income countries. Potential barriers to achieving this have been discussed, and how these might be removed, thus enabling policies to create value in regard to business ecosystems [99]. Interestingly, although European Union countries have been increasing their recycling of plastic waste, they have also been generating more of it, as shown in an infographic published by the European Parliament [100]; hence, the European Commission has outlined an EU Plastics Strategy for improving the situation [101].

In a mathematical study [102], it was demonstrated that the only way to reduce the amount of plastics that finally end up in landfill or are incinerated is to produce less in the first place: what is not created does not need to be disposed of. Thus, recycled material must displace primary production, but since this is driven by market forces, there is no guarantee it will happen. To assume, incorrectly, that all recycled plastic avoids disposal underestimates the environmental impacts of the product system. It is proposed that "scholars and policy makers should focus on finding and implementing ways to increase the *displacement potential* of recyclable materials rather than focusing on disposal diversion targets" [102]. Finally, recycling of plastics does nothing to tackle the seemingly relentless global demand for these materials, and hence, if current lifestyles are to be maintained, appropriate changes must be made across the entire manufacturing chain. Plastic recycling is also of significance to climate change, since it has been estimated that "If all plastic were recycled, this could result in mean annual savings of 30–150 million tons of CO_2, equivalent to stopping between 8 and 40 coal-fired power plants globally" [103].

8. Improved collection and processing of end-of-life plastics

Based on data from 2019, globally, the percentage of plastic waste that is landfilled, mismanaged, incinerated, and recycled is 49%, 22%, 19%, and 9%, respectively [104]. In a recent study [105], it was found that macroplastic emissions are highest across countries in Southern Asia, Sub-Saharan Africa, and South-Eastern Asia. India is at the top of the list, with 9.3 Mt year^{-1}, which amounts to almost one-fifth of global plastic emissions. Whereas China had previously been placed at the top of the world list of plastic polluters [106], this new study puts it in only fourth place, which is lower than both Nigeria and Indonesia. In part, China's movement down the league reflects a much better control of landfill and incineration processes [107]. However, uncontrolled land disposal sites in India outnumber sanitary landfills by a factor of 10 to 1 [108], and there is evidence that open burning of uncollected waste, or waste recycled by the informal sector, is not included in the officially reported figures, despite the claim of a 95% collection rate [109]. Hence, the 0.12 kg per capita of waste generation, cited from official data, seems on the low side, whereas the present study [105] comes out at 0.54 kg cap^{-1} day^{-1}, which agrees more closely with other estimates [109–111].

Thus, improving management of plastic waste is critical for ameliorating it as an environmental pollutant [112]. This demands more effective collection of plastics, particularly in those countries that are the greatest emitters, and in poorer nations, where necessary facilities are lacking, due to limited resources and infrastructure that needs to be improved [113]. It has been stressed that, in developing nations, the informal recycling sector should be empowered to provide a hands-on approach to increase plastic recycling rates and urge forward a recycling economy [114]. Thus, the effectiveness of a data-driven waste collection, two-tier optimization approach has been presented, which integrates clustering and optimization to maximize waste collection while minimizing the travelling distances associated with this [115].

There is a lack of possible sites to dispose of plastic waste in poorer countries, which instead adopt incineration or open burning to reduce its quantity. However, doing so releases significant amounts of greenhouse gases, COx, NOx, and other poisonous gases [116]. In addition, poorer people burn waste plastic, often scavenged from landfills, as cheap fuel for cooking [117]. The harmfulness of burning plastic, from a climate change perspective, has been emphasized by the observation that plastics are just “fossil fuels in another form” [118]. Since the vast majority of plastics are derived from fossil sources, in the present context, this is true; in 2022, 44% of plastics were derived from coal, 40% from petroleum, 8% from natural gas, 5% from coke, and 1% from other sources [96]. Hence, a more integrated approach is necessary to minimize plastics ending up as waste in the first place. The amount of plastic waste tends to be greatest in low to middle-income nations, and while each nation must adopt improved waste management at the domestic level, it is also necessary for richer countries to invest in appropriate infrastructure for waste management in poorer regions [119].

Using detailed global and regional plastics datasets, coupled with socioeconomic data, machine learning has been used to predict that, following “business as usual”, annual mismanaged plastic waste (i.e., that is not recycled, landfilled, or incinerated) will nearly double to 121 Mt by 2050. However, it is predicted that, by combining different policy interventions, mismanaged plastic might be decreased by 91%, accompanied by a one-third reduction in plastic-related greenhouse gas emissions [120]. An opportunity to reshape these outcomes is presented by the United Nations’ “global plastic pollution treaty” [23]. Since effective collection of plastics is a critical component for managing plastic waste, in recent years, a number of countries have transformed their plastic collection systems [121–123]. However, as the feedstock for the sorting process becomes more complex and leads to cross-contamination within the sorted fractions, aspects such as packaging design, collection, recycling rates, and, finally, the quality of sorted plastics must all be integrated. To handle the vast amount of data that will need to be processed, it is proposed that multi-sensory artificial intelligence (AI) could be an effective means to increase the efficiency of recycling plastic waste and assist the development of a plastics circular economy [123]. Emerging plastic waste management technologies have been evaluated from both an economic and environmental perspective. It was shown that those recycling programs currently based entirely on mechanical recycling are associated with higher costs, but can achieve the smallest life cycle emissions, irrespective of whether the waste plastic streams are landfilled or incinerated for waste-to-energy conversion. To prepare for a future with greatly enhanced recycling rates, it is proposed that those systems employing fully commercialized dissolution/precipitation and chemical recycling can achieve reductions both in costs and emissions [124].

Similarly, a lifecycle analysis has been made of chemical recycling via pyrolysis of mixed plastic waste, in comparison with mechanical recycling and energy recovery. It is concluded that 50% less CO_2 eq is emitted from pyrolysis than from energy recovery, but that the overall global warming potentials of the two approaches are comparable. However, pyrolysis is found to have, by far, the greatest additional (environmental) impacts, over mechanical recycling, energy recovery, and the production of virgin plastics, although the results depend very much on those assumptions made regarding geographical location, the energy mix, and quality of the recycled material being processed [125].

9. Plastics we can’t (easily) manage without

As we see in Section 13, reducing our use of plastic will require fundamental behavioral (and societal) changes, but for the most part, it would be best to reserve plastics for those purposes where they are not easily replaced by other materials [17]. There is an element of subjectivity over which plastics are essential or not, and to assist in making such choices, George has proposed that Maslow's hierarchy of needs be used to decide which plastics are essential or merely desirable/convenient, and hence if they can be (a) avoided by using a different product or activity, (b) reduced through design, or (c) replaced by another material. Key areas identified are food production, medicine and health, and electronics, asking what changes can be made without causing serious negative consequences for society [126]. That we cannot live entirely without plastics is the subject of an article from the think-tank Chatham House, which once again emphasized their criticality for healthcare, food safety, and other safety applications ranging from cycling helmets to electrical insulation. However, a hugely complex variety of plastics is currently being produced, often not in forms that can easily be recycled. The report proposed that the number of plastics produced be reduced to perhaps 10–20 key polymers, which can be easily identified, sorted, and recycled, from the thousands now available. However, resistance to this strategy is to be expected, since it would reduce profits for the fossil fuel industry, as primary producers, and for others who rely on a rapid turnover business model, such as fast fashion or “on-the-go” consumables such as disposable cups [127].

Some of the many specific uses of plastic that cannot (easily) be avoided include sterile, single-use medical items such as surgical gloves, syringes, IV bags and catheters, vaccines and bandages, PPE facemasks, and protective clothing (i.e., as used during the COVID-19 pandemic). Sterile storage and lightweight transport of medicines and medical supplies, including vaccines and bandages, are also facilitated by plastics, although the absolute necessity for their use throughout the healthcare system has been challenged [128].

10. Eliminating unnecessary use of plastics

Since the most effective action would be to avoid single-use plastics, the European Commission has imposed a ban on single-use plastic plates, cutlery, straws, balloon sticks, and cotton buds, which cannot be placed on the markets of the EU Member States. This same restriction also applies to cups and food and beverage containers made of expanded polystyrene, and to all products made of Oxo-degradable plastic [129].

The European directive on single-use plastics identifies that [130]:

"The priority should be to reduce the use of unnecessary plastic while avoiding substitutes which have worse environmental impacts. One way is to move away from single-use plastics towards reuse alternatives such as reusable coffee cup schemes or refill isles in supermarkets.

Plastics must also be captured before they become waste and pollute the environment through incentives such as deposit return schemes.

Finally, plastic products need to be redesigned with recycling in mind using individual polymer plastics. The European Union (EU) is leading the way currently, setting an ambitious target to make all plastic packaging fully recyclable by 2030."

The most problematic and unnecessary plastics have been identified to be #6 PS, #3 PVC, #7 PC, and black plastics, due to the toxic materials associated with them and the fact that they are not easily recycled. While less toxic, more recyclable plastics need to be used to manufacture essential single-use items, it is also critical to create systems that reduce all single-use packaging by enabling "reuse" as far as possible [131]. However, a compromise exists regarding overall impacts and climate change over which materials to use, i.e., plastic containers may be better for some purposes, but end-of-life issues also need to be addressed [132]. This point is reinforced by another study, showing that in 15 out of 16 applications considered, smaller greenhouse gas emissions resulted from a plastic product than the proposed alternatives. Hence, caution is urged in trying to reduce the use of plastic by adopting plastic-free substitutes that actually increase greenhouse gas emissions [9].

11. A new plastics economy

Alternative approaches to dealing with plastic waste tend to involve a change in perception, viewing it not as a problem but a resource and working within the framework of a circular economy [15,133,134]. The vision of "A New Plastics Economy" [15] is that plastics never become waste or pollution; the means to achieve this agree with the following set of rules [17]:

Eliminate all problematic and unnecessary plastic items.

Innovate to ensure that the plastics we do need are reusable, recyclable, or compostable.

Circulate all the plastic items we use to keep them in the economy and out of the environment [15].

In their perspective article, Forrest et al. stressed the imperative for voluntary contributions from industry to eliminate plastic pollution and to drive the circular plastics economy [135]. In October 2018, the Ellen MacArthur Foundation and the UN Environment Programme launched the New Plastics Economy Global Commitment. This brought together businesses and governments (representing 20% of all plastic packaging produced globally) along with other organizations, globally, in a commitment to change how we produce, use, and reuse plastic, to prevent it from becoming waste or pollution at any stage. As of November 2023, more than 500 signatories had been collected [136].

Although technological advances are possible [7,17,87–89,137] in the manufacture of conventional plastics, better design to allow improved recycling, and some use of bio-based polymers ("bioplastics"), along with enhanced collection and (chemical) recycling methods, largely, the intention is essentially to preserve business as usual. However, various lifecycle analyses identified, as a very significant factor, the importance of reducing our demand for plastic materials per se [137–139]. The "Blue Planet Effect" [19] has prompted several UK supermarkets to offer plastic-free alternatives [17], although such "loose" fruit and vegetables may cost more than their plastic-wrapped equivalents [140]. It is commonly argued that plastic packaging results in food lasting longer, with less being wasted [141], and there is some truth in this. However, this mainly applies to an industrial food production and distribution network, on a global scale, and also causes more food to be bought by consumers, e.g., "buy one get one free" deals, a significant amount of which is then actually discarded [141]. The quantity of food wasted from the present system is an enormous and complex problem whose origins vary from nation to nation. At least 40% of the food produced in the world is lost or discarded along the value chain, which reveals a major flaw in global food systems [142]. In contrast, more food that is locally grown tends to be eaten, and more quickly, meaning that less plastic packaging is necessary. In addition, transportation requirements are reduced, with fewer vehicles, and hence less plastics are needed to construct them; this also reduces MP pollution from the abrasion of tires, brakes, and road markings [7,141].

Each year, close to half a trillion plastic water bottles are sold globally, and local authorities have, in some areas, introduced public drinking fountains, meaning that they can be replaced by refillable water bottles [7]. The Refill campaign is another similar initiative, and those businesses that signed up to this will allow customers to refill water bottles on their premises, rather than buying plastic bottles that are later thrown away. This scheme has since been adopted in other countries [143].

While plastic bag reduction campaigns have been widely promoted, and some have been initially effective, e.g., adding a small charge to the consumer for each bag [144], replacing them with equivalents made from other materials is contentious. For example, there are highly varying estimates for how many times a cotton bag needs to be used to have the same climate impact as a single-use plastic bag. A UN Environment Programme report concluded that it is 50–150 times [145], while a Danish Environmental Protection Agency Report [146] is widely quoted as having arrived at a figure of 7,100 times (or 20,000 times, for an organic cotton bag). The proverbial devil is in the details, however, and these very high figures refer to the ozone-depleting effects of the different materials. In terms of the bags' greenhouse gas emissions directly, the Danish study comes out at 52 times, more in line with the UN estimate. The alternative, heavier-duty plastic "bag for life" scheme is, apparently, not working, as people seem to be buying more of them and throwing them away after only a few uses, defeating the objective of curbing overall plastic waste by avoiding thinner, single-use bags [147].

12. Bioplastics (bio-based polymers)

The International Union of Pure and Applied Chemistry [148] provided the following definition and qualifications for bioplastics (bio-based polymers):

"[A] *Biobased polymer* [is] derived from the *biomass* or issued from monomers derived from the biomass and which, at some stage in its processing into finished products, can be shaped by flow.

Note 1: Bioplastic is generally used as the opposite of polymer derived from fossil resources.

Note 2: Bioplastic is misleading because it suggests that any polymer derived from the biomass is *environmentally friendly*.

Note 3: The use of the term "bioplastic" is discouraged. Use the expression ‘biobased polymer’.

Note 4: A biobased polymer similar to a petrobased one does not imply any superiority with respect to the environment unless the comparison of respective *life cycle assessments* is favourable.” [149].

Bioplastics have been proposed to reduce both the burden on the world's petroleum resource base for making plastic materials and environmental impacts. The most common are polylactic acid (PLA), polyglycolide (PGA), polycaprolactone (PCL), polyhydroxyalkanoates (PHA), poly (butylene succinate) (PBS), and poly (butylene adipate-*co*-terephthalate) (PBAT) [150]. PLA is considered to be among the most promising, since it is manufactured from lactic acid, which can be derived sustainably from different crops, including corn [150,151]. Nonetheless, currently, less than 1% of total global plastic manufacture is accounted for by bio-based polymers [152].

However, considering that 2.47 kg of maize biomass is needed to produce 1 kg of bioplastic, requiring 1.7 m^2 of land, a yield of 5.9 t/ha may be estimated [153], implying that to replace the 460 million tons of plastics currently produced from petroleum would require *ca* 78 million ha of arable land, or 5.6% of the total available arable land on Earth. In order to fulfil a projected growth in production/demand to around 1200 million tons by 2060, the area of arable land would also need to triple. As a material, PLA has good mechanical strength and low toxicity and can be used in biomedical applications and for the fabrication of packaging [154]. Moreover, when used to make medical implants, such as anchors, screws, plates, pins, rods, and meshes, over a period of six months to two years, PLA decomposes to form lactic acid as a non-toxic product [155]. As the material decays, the load is steadily transferred to the body (e.g., to the bone) as the particular area heals [156]. PLA does, however, have a relatively low glass transition temperature of around 60 °C, which limits its use for purposes that require higher temperatures [157].

While the labels “100% compostable” and “100% degradable” feature widely on items made from PLA, such as tumblers for drinks, both descriptors may be misleading. In particular, although the term “biodegradable” means that the component polymer molecules are expected to break down eventually under the influence of microbial action, many biodegradable “bioplastics” require industrial composting facilities to fully decompose [158,159]. Thus, they may not decompose effectively in a garden compost heap/bin, instead emitting methane during a much slower degradation process [160]. Biodegradable plastics that are described as “compostable” must adhere to more rigorous criteria, for example, the European Standard EN13432 [161] certification that they break down under industrial composting conditions [162] in less than 12 weeks. Industrial composting facilities operate at around 60 °C (or higher) and provide appropriate microorganisms, moisture, and air, which support efficient conversion of organic waste to nutrient-rich material that can be used to nourish and enrich soil (i.e., as normal compost [141]). In the open environment, biodegradable or compostable plastics may fragment to form MPs (as do petroleum-based plastics) [163] and further to NPs, as studied for polyhydroxybutyrate (PHB), which can be toxic, for example, to freshwater ecosystems [164]. When contained within a composting facility, this is avoided [163].

Biodegradable polymers could contribute to reducing the environmental problem of plastic pollution, although further advances in R&D are required to implement them on a significant scale [137,165]. Matching the specific properties of a petroleum-derived plastic with a replacement "biological" alternative is another issue. For example, it has been argued that entirely substituting naturally sourced fibers for polyester and polyamide is not possible, because they need to be robust for most applications, e.g., outdoors, but this contradicts the need for the natural materials to also be readily decomposable [166].

13. Behavioral changes

Since plastics are such a deeply entrenched feature of our modern, consumer society, to avoid them entirely seems a remote prospect, at least without drastic changes to the fabric and mechanism of that society [126–128]. The following articles endorse this but also offer hope that while finding a single solution may be difficult, by integrating different strategies, both physical and psychosocial, the problem of overconsumption might be addressed, with plastic reduction as part of a broader aspect of reducing materials use and waste production ("ecological overshoot") [167]. Thus, the One Planet network and the Stockholm Environment Institute have produced a report, which offers a practical guide to getting people to reduce their use of plastic and for effectively organizing and running campaigns, in the wider sense [168]. One study on behavioral changes as a means to curb plastic consumption obtained mixed results [169]. It was determined that a design of necessary interventions would be best made in partnership with a variety of stakeholders, and that those most effective are likely to integrate a range of methods, both regulatory and persuasive (i.e., "stick and carrot") [169]. From a sample of >500 residents in Thailand, it was determined that while morality over environmental protection better justified the participants' behavior overall, in regard to reducing their single use of plastics, rural citizens were more influenced by rationality, while those living in a city were apparently more driven by morality [170]. Since educational establishments are critical nurturing grounds for a generation to emerge with an ideology that values and protects the environment, underpinning factors toward their reduction in single-use plastics were explored among Thai university students. On the basis of the Theory of Planned Behavior, the influence of psychosocial factors, such as attitudes, perceived behavioral control, and subjective norms, was examined and found to vary in importance at particular phases of the behavioral change process [171].

Although it is necessary to adopt a "sufficiency-oriented lifestyle" as a part of acting to curb overconsumption, social difficulties are experienced by many individuals who attempt to do this. By combining perspectives of care and sufficiency-oriented lifestyle changes, some understanding has been offered of why such social impedances occur, along with potential strategies to overcome them, and how social relations might instead be used to support patterns of lower consumption [172]. The broader picture of systemic human behavioral traits and the polycrisis has been addressed, of particular importance being those which have become maladaptive in the context of modernity; in particular, warfare, resource overexploitation, and human cognitive biases. On the basis of key literature articles, behavioral traits are highlighted that underpin these maladaptations, and which are further proposed to offer leverage points in the global system where the likelihood of a polycrisis might be alleviated [173]. Similarly, Merz et al. [174] identified that the root of human ecological overshoot lies in a (maladaptive) behavioral crisis, driven in part by advertising, but that those same mechanisms may also provide means for throwing into reverse the three "levers" of overshoot—consumption, waste, and population. The authors further identified that a gulf in communication exists, "between those that know, such as scientists working within limits to growth, and those members of the citizenry, largely influenced by social scientists and industry, that must act". Hence, bridging this discontinuity is an essential strategy for making necessary systemic changes [174].

14. The oil, plastics, energy nexus

As already noted, the vast majority of plastics are derived from fossil sources, mainly coal and petroleum [96]. It has been argued [10] that the recent dramatic increase in plastics production is part of a deliberate strategy by multinational fossil-carbon corporations, which, in integrated form, produce coal, oil, and gas and additionally manufacture plastics. Thus, while there is a reduction in the production of fossil fuels per se by particular enterprises, their manufacture of plastics is increasing in order to maintain and expand the overall product base [10].

The Ellen MacArthur Foundation's "New Plastics Economy" report [15] concluded that, in 2014, the plastics industry consumed 6% of the global oil supply (including natural gas liquids). They further estimated that, in 2050, 20% of the world's available oil supply will be consumed by making plastics [15]. However, such reasoning assumes that the oil supply will remain sufficiently robust for these projections to be realized, which is not guaranteed, as a result of limitations in global oil production [175–178]. Evidence has suggested that growth in the global oil supply is being substantially maintained by fracking, mainly in the US, but this industry may not be able to sustain its output, leading to a supply downturn at some point from 2025 to 2030 [179].

Future restrictions may limit how much plastic can actually be made, given other demands for fossil fuels [176,179], as well as considerations over reducing greenhouse gas emissions. The implication, therefore, is that, along with limits to possible bioplastics production, there may be less plastic available overall, which, therefore, should be "saved" for critical applications where there is no ready substitute, e.g., medical/healthcare industry, electronics, clean water, clean medicine, and clean food.

15. Conclusions

In 2019, 460 Mt of plastic was produced, a number projected to reach 1,230 Mt by 2060. Plastic waste amounts to more than 400 Mt/a, roughly half from single-use items such as packaging, a number that is expected to exceed 1,000 Mt by 2060. By 2050, 20% of the world's oil supply is predicted to be consumed by plastics, along with 15% of the global carbon budget. Microplastics (MPs) cannot be avoided entirely, so long as we keep using plastic materials that go through a wear and tear process, including vehicle components (tires, brakes, upholstery, etc.), road markings, marine coatings, clothing, paints, agricultural films, and synthetic textiles. Plastic pollution poses significant and grave health risks, impairs biodiversity, and contributes to emissions/climate change along the entire "cradle-to-grave" chain. Consequent damage to ecosystems impairs their ability to absorb carbon, e.g., phytoplankton and soils.

While the amount varies from region to region, on a global basis, merely 9% of plastic waste is recycled. A more effective interception and collection of plastic items after their use is critical to reduce their environmental burden. End-of-life aspects need to be designed into a plastic item when it is created. Contaminant materials that make recycling difficult should be avoided.

Plastic waste should be ameliorated, mainly by curbing the overall use of plastics per se, through the approach: Refuse, Reduce, Reuse, Repurpose, and Recycle (as a last resort). Wasteful (unnecessary) and single/short-term-use plastics, especially disposable packaging, must be minimized. Limits to the production of bioplastics, along with an ultimately declining supply of fossil fuels, suggest that relentless expansion in the availability of plastics may, in any case, be unlikely, and that a combination of more effective use, material substitution, and behavioral changes is the more viable way forward. Plastics should be "saved" for critical applications, where there is no ready substitute, as in healthcare, food/water provision, and electronics.

This approach also accords with the need to respect overall resource limits and planetary boundaries. Means to leverage behavioral changes regarding consumption patterns are required to bring humankind to below ecological overshoot and begin healing the current polycrisis. Achieving a sustainable future also likely involves living in a more locally focused way, including local food growing. This will further reduce both the need for plastic packaging and MPs emissions from vehicles, along with a lower dependence on food imports and other supply chains, which may fail as a result of climate change impacts on agriculture and eventual restrictions to the global oil supply.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors assert that there are no conflicts of interest regarding the publishing of this work.

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