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Plastics and the Environment

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Plastics and the Environment

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Abstract

Plastics are persistent and pervasive throughout the environment and have now been reported from the deepest parts of the ocean to the tops of the highest and most remote mountains. There is a body of information on the sources, degradation, and transport of plastics as well as a variety of research carried out to investigate the ecotoxicological and wider ecological consequences of plastic ingestion and accumulation. Such knowledge has been obtained with developments in field and laboratory methods for plastic identification and then well-publicized in the media and wider public communications. However, although there has been a large focus on plastic pollution within the past decade, there is plenty that we do not yet know. Even within the past five years, sources of microplastics (1 µm–5 mm) to the environment have been confirmed that have not previously been considered, for example, road paints and tire wear particles. Initial research focused on plastic in the marine environment, but now our understanding on the impacts in terrestrial and freshwater environments is growing. There is a substantial lack of basic science focused on the efficiency of solutions aimed at mitigating plastic pollution. This review highlights some recent (past five years) research on plastics in the environment; including investigations in accumulation, sources, distribution, impacts, solutions and provides directions for future work.

HISTORY

End of life plastic items are now a major component of waste, and substantial quantities are accumulating as litter in the environment (1). To understand their sources, consequences, and accumulation in the environment, we must first place plastics into context within the wider topic of litter. Plastics are lightweight, inexpensive, and highly durable materials used in various products. Subsequently, plastics, in particular single-use plastic packaging, have contributed to almost every aspect of modern life, displacing other materials used in various facets of society, such as in health care, agriculture, transport, and construction.

Plastics consist of synthetic polymers and are used to create a multitude of products that bring numerous societal benefits. There are many variants, with the most common plastics including polyethylene (PE), polypropylene (PP), polyvinyl chloride, polyethylene terephthalate (PET), and polystyrene (PS). Some applications of plastics have a long service life, such as components in vehicles or those used in the construction industry. However, approximately 40% of all the plastic produced is used for packaging, which is predominantly single use (2).

The versatility of plastic materials has resulted in a substantial increase in their use from 5 million metric tons (Mt) globally in the 1950s to more than 367 million in 2020 (2, 3). Following this, it has also been predicted that plastic pollution from 2016 will triple toward 2040, if measures are not taken urgently (4). Although the timeframe for the complete mineralization is unknown, it has been suggested that all of the conventional plastic ever made is still on the planet unless it has been burnt (5). Mineralization is the microbial conversion of plastic and all its organic constituents to carbon dioxide, new microbial biomass, and mineral salts under oxic conditions or to carbon dioxide, methane, new microbial biomass, and mineral salts under anoxic conditions (6).

As a result of its multiple sources and transport pathways to the environment, plastic debris contaminates the environment on a global scale, from the Antarctic to the Arctic, the deep sea to near the summit of Mount Everest (7–10), and even within our atmosphere (11–13). Plastic debris has been identified as a major global problem by the United Nations (UN) Environment Assembly and in the 2015 G7 Leaders' Declaration. In March 2022, UN member states adopted a mandate for an International Negotiating Committee to develop a legally binding UN treaty on plastic pollution that addresses the entire plastics life cycle from source to sea (14). In this article, the term debris is defined as items occurring in natural environments without fulfilling an intended function; we use the term interchangeably with litter and/or contamination (15).

Plastic contamination of the marine environment has been increasingly well documented since the 1980s, which is roughly 30 years after the start of mass production (16, 17). It has been estimated that ~8 million Mt of macroplastic (18) and 1.5 Mt of primary microplastic (19) enter the ocean annually. There is now growing evidence of plastic contamination in terrestrial, aquatic, estuarine, and atmospheric environments (12, 20, 21). As such, the past two decades have seen a significant increase in plastic debris research seeking to understand the sources and characteristic properties of the material within the environment (i.e., material type, size, and shape). Research into the transportation mechanisms, accumulation, and impacts has also increased markedly (22). Additionally, the pollution of the environment with plastics has garnered significant public attention in the past decade, including popular campaigns to reduce single-use plastics (e.g., National Geographic's Planet or Plastic? campaign and the Plastic Free July movement) and widely viewed documentaries (e.g., *Blue Planet*) (23). This review highlights recent key research on plastics in the environment, including accumulation, sources, distribution, impacts, and solutions and provides directions for future work.

TERMINOLOGY

Due to the various sources, polymer types, and sizes, a range of terminology has been used to describe plastic debris in the environment (15). Plastic debris can be defined in numerous ways including by origin (e.g., debris from the land, fishing-related or sewage-related debris), size, shape, color, polymer type, or original usage. As plastic debris has been reported across a wide range of sizes from discarded fishing nets that can be thousands of meters in length to microscopic fragments just microns in diameter (24, 25), size is one of the commonly used classifications. Four categories that are widely used to describe the size of plastic contamination include macroplastic (>20 mm diameter), mesoplastic (5–20 mm), microplastic (<5 mm), and nanoplastic (1–1,000 nm).

Macroplastic refers to plastic items larger than 20 mm. Due to its high visibility, contamination of the environment by macroplastic may be perceived as one of the most concerning forms of plastic pollution, and its accumulation has been reported in a wide range of habitats (26, 27). Cleanup campaigns typically focus on these larger items, and there is wide geographical variability in abundance, which increases the difficulty of analyzing potential trends. However, due to the size of this debris, it is often possible to categorize items according to their original usage, for example, packaging-, fishing-, or sewage-related debris.

Microplastics (particles less than 5 mm in diameter) accumulate from primary and secondary sources. The distinction between the two is based on whether the particles were originally manufactured within the microplastic size range (primary) or whether they have resulted from the fragmentation of larger items (secondary). Although the term microplastic was first used to describe microscopic fragments of plastic in 2004 (28), it is apparent that microplastics are a ubiquitous component of anthropogenic debris in different environments and have been reported since the 1970s (8, 29–32). Microplastics substantially outnumber large plastic items in marine systems, but only account for a small proportion of the total mass of plastic in the ocean (33, 34). However, even if we were able to stop the discharge of macroplastic litter into the sea today, ongoing degradation of the larger litter items already at sea and on beaches would likely result in a sustained increase in the quantity of microplastics for years to come.

Nanoplastics are typically regarded as pieces less than 1,000 nm. Similar to microplastics, nanoplastics can result from the erosion or breaking down of larger plastic debris and are consequently highly polydisperse in physical properties and heterogeneous in composition (35, 36). However, research on nanoplastics is still in its infancy and, due to the limitation of technology, the degradation processes and degradation rates of microplastics to nanoplastics are not yet clear (37).

Although size is the most common descriptor, there are no universal conventions on nomenclature, and this challenges intercomparability of the data (15). Although this is inherent in any emerging research field, ambiguous terminology results in confusion and miscommunication that may compromise progress in research and mitigation measures. Therefore, we need to be explicit on what exactly we consider plastic debris. To promote consensus building, Hartmann et al. (15) have provided a framework for defining and further categorizing plastic debris. They identify the following three defining criteria that can be used in such a framework: (*a*) present in natural environments without fulfilling an intended function, (*b*) solid, and (*c*) insoluble at 20°C; the four classifiers they recommend to categorize plastic debris are (*a*) size, (*b*) shape, (*c*) color, and (*d*) origin.

ACCUMULATION AND DISTRIBUTION

The accumulation and distribution of plastics in different environments worldwide has been reviewed in many previous works (38, 39). Arguably, our understanding of the accumulation of plastic in the environment began with a focus on aquatic debris within the past decade (28, 32, 40). Research by Kasavan et al. (41) explored the global trends of plastic pollution in water ecosystem research between 2000 and 2020 using bibliometric analysis and found in the first 11 years (2000–2010) research increased slowly over time, despite some fluctuations and fewer publications recorded. During the next ten years (from 2011 to 2020), the number of research articles quickly increased and gained substantial attention; subsequently, 2,110 articles out of 2,182 were published during this period, representing 96.7% of all studies included. During these initial years (2000–2006), most research focused on quantifying marine debris and the impact of plastic pollution on aquatic life (42, 43). However, since then, there has been growing evidence that plastics are also accumulating in different areas such as terrestrial (44, 45) and atmospheric environments (12).

Marine debris originates from a wide range of sources, both terrestrial and marine, and is found not only in coastal waters (46, 47) but extends to the open oceans (33, 48) and the seafloor (49, 50). Once in the marine environment, plastic can become widely transported due to its properties of buoyancy and durability. For example, macroplastics and microplastics abundance have even been observed four and 15 times more, respectively, at the coastal turbulent zone created by the combination of breaking waves than in the outer nearshore waters (51); this suggests that plastic accumulation is driven by the physical properties of the plastic particles such as density, buoyancy, and surface area. Particles of low density tend to stay in surface water. Denser particles are more likely to transfer vertically; for example, 5 mm polyoxymethylene particles, which have a density of 1.6 g cm^{-3}, have been reported to settle through the water column of ≈250 m in the central Gotland basin in <18 h (52). Biofouling (i.e., rapid colonization of submerged plastic surfaces by microorganisms) of plastics may also act as a mechanism increasing sedimentation but also their horizontal distribution (53). Microbial growth (biofilm) on the surface of low density microplastics can lead to an overall density increase and hence cause sinking (54). Moreover, the development of complex microbial biofilms facilitates the adhesion of suspended dense materials such as marine snow and iron hydroxides, which further increases the overall mass and speeds up the sinking of microplastics (55).

Riverine transport is a key pathway that transfers plastics from land to marine environments.

Napper et al. (31) estimated that the Ganges, with the combined flows of the Brahmaputra and Meghna rivers, could release up to 1–3 billion microplastics into the Bay of Bengal (northeastern portion of the Indian Ocean) every day, with microplastic concentration increasing from source to sea. Such research provides the first step in understanding how major rivers may contribute to oceanic microplastic. Urban surface runoff may be a large contributor to plastic in rivers. For example, researchers have reported that approximately 42% of microplastics in European rivers are tire and road wear particles carried by urban runoff (56), and 62% of microplastics in the Baltic Sea are predicted to have been transported via urban stormwater runoff including sewer overflow (57). However, there is discrepancy between estimates of the amount of microplastics supposedly exported by rivers to the ocean and the microplastic stocks accumulating at the ocean surface that has triggered the idea of a "missing" ocean plastic sink (28, 33).

Plastics can also be potentially transported by wind due to their low density and light weight. Subsequently, the atmosphere has been reported to be an important pathway by which suspended particulates can be transported regionally and even on a global scale (11, 12, 58), and microfibers from clothing are suspected to be large contributors (8, 59). Atmospheric deposition rates for microplastics (predominately fibers) have been studied in urban areas [ranging from 10 m^{-2} d^{-1} in Gdynia, Poland (59), to 771 m^{-2} d^{-1} in Central London, United Kingdom (11)] and in remote regions [ranging from 12 m^{-2} d^{-1} in Mount Derak, Iran (60), to 365 m^{-2} d^{-1} in the French Pyrenees (10)]. Despite Mount Everest's high altitude and location away from major population centers, Napper et al.'s (8) study reported the highest altitude microplastics ever recorded (8,440 meters above sea level), which were predicted to be transported by wind currents and direct deposition from climbers. As such, estimations of microfiber pollution entering the environment may be underestimated, as not all sources, such as atmospheric deposition, are included (8).

Additionally, although plastics in most scenarios have been transported from land to aquatic environments, they can also remain on land or be transported from water to land or atmosphere. Plastic contamination of terrestrial environments, in particular agricultural soils, has only recently received attention but accounts for a substantial proportion of the total released plastic to the environment (61, 62). For example, Fuller & Gautam (63) detected 0.03 to 6.7% of plastic in soils of an industrial area. Sewage sludge from wastewater treatment plants is another pathway for plastic to enter the terrestrial environment (63). Sewage sludge can be diverted to landfill and incineration into use for energy production. However, in some countries, up to 80% of municipal wastewater sludge is reused in agriculture, where a substantial amount of plastic can be found in the biosolids: 4,200–15,800 particles kg^{-1} (64).

From the perspective of plastic being transported back to land from water, research has focused on quantifying and characterizing litter found within coastal environments. For example, Nelms et al. (65) analyzed data collected over a decade (2005–2014 inclusive) by volunteers from a UK charity (Marine Conservation Society) during beach litter surveys along the British coastline. The aim was to increase the knowledge on the composition, spatial distribution, and temporal trends of coastal debris. Their research found that plastic was the main constituent of anthropogenic litter on British beaches and the majority of traceable items originated from land-based sources. These items may have washed back onto the beach after being in the marine environment for a period of time (65). Additionally, Wright et al. (66) investigated abandoned, lost, or otherwise discarded fishing gear (ALDFG) on northern and southern beaches of the English Southwest Peninsula, finding a mean ALDFG abundance of 1.74 ± 0.44 $person^{-1}$ m^{-1} day^{-1} (units standardized by person and time). Allen et al.’s (67) research also suggested that plastic particles could be leaving the sea and entering the atmosphere along with sea salt, bacteria, viruses, and algae. They report that microplastics potentially could be released from the marine environment into the atmosphere by sea spray, giving a globally extrapolated figure of 136,000 ton/year blowing on shore.

FIELD AND LABORATORY METHODS FOR SAMPLING AND IDENTIFYING PLASTIC

Quantifying the distribution of plastic is strongly influenced by the sampling method chosen, and this can vary by environment type and debris size. At present, most methods depend on some degree of visual selection of items or particles. The most direct visual selection methods occur for macroplastics in surveys on land (68, 69) but can also occur at the sea surface from ships or aircraft, and on the seafloor by divers or towed underwater camera systems, in which only debris visible to the observer (for direct observation) or to the analyst (for photographs or video) is recorded (70).

However, extracting smaller plastic particles from environmental matrixes can have limitations. For example, the mesh size of nets used to sample surface water (31) or the sieves used in sampling beach sand (71) primarily determine the lower-size limit of sampled microplastics. Lindeque et al. (72) found that sampling for waterborne microplastic using nets with a 100 µm mesh resulted in the collection of 2.5-fold and 10-fold greater microplastic concentrations compared with using 333 and 500 µm meshes. Researchers have reported nanoplastic particles also occurring in the environment, but analytical methods for the separation, concentration, and identification of nanoplastics are lacking. There have been, however, developments in methodology; for example, Cai et al. (73) spiked river water with PS fragments (<1,000 nm) at an environmentally relevant concentration (10^8–10^9 particles/L), and they successfully separated the fragments with a high recovery rate (87.1%) after undergoing a process with ultracentrifugation. Fieldwork developments have also become more creative in finding ways to quantifying plastic from environmental samples; for example, Goßmann et al. (74) conducted research using spider webs to gain insights into the spatial and temporal trends of microplastics in urban air.

Environmental conditions may also influence the data collected. Patrício et al. (75) investigated the effects of seasonal factors on the characteristics of (micro)plastics in a sandy beach in Aveiro, Portugal. They reported that PE pellets were more abundant during wet seasons, and fragments and pellets of both PE and PP characterized dry seasons. A higher concentration of plastic fibers was also found during dry seasons, likely from their accumulation and beach use during bathing season (76).

There have also been technological advances that aid understanding of the abundance and distribution of plastic. Dasgupta et al. (77) investigated the relationship between seasonal rainfall and plastic waste transport using high-resolution satellite imagery from the European Space Agency’s Sentinel-2 platform. Subsequently, they report that high-resolution satellite imagery offers new opportunities for understanding the spatial and temporal components of marine plastic pollution. Another example of technological advances includes research by Duncan et al. (78), who undertook a proof of concept study by using open source tracking technology (both Global Positioning System cellular networks and satellite technology). This technology, which has been successfully used in many animal movement studies, was used to track the movements of individually tagged plastic litter items (500 ml PET drink bottles) through a major river system (Ganges River) and the Bay of Bengal. The maximum distance tracked was 2,845 km over a period of 94 days. This research demonstrates the potential widespread use of this open-source technology to significantly increase our understanding of the location of accumulation areas and the timing of large inputs of plastic pollution into the aquatic system.

Identifying temporal trends of litter necessitates large long-term datasets with comprehensive spatial coverage, which can be costly, time-consuming, and labor-intensive to acquire (68). Subsequently, there has been a rise in citizen science (the practice of nonspecialist individuals or members of the general public participating in scientific research in partnership with scientists) to develop large-scale and long-term monitoring datasets to support scientific needs and planning decisions (79, 80). This expansion in citizen science also reflects numerous other factors, including (*a*) the need to make research more societally relevant (81), (*b*) increased public awareness of environmental issues, and (*c*) the development of assisting technology (e.g., low-cost sensor networks, smartphones) (82). For example, mobile phone applications (apps) are popular for citizen science because they allow for quick, easy, and often real-time data submission. They can also improve spatial information accuracy, collect data from those who are not participating in organized activities, and increase levels of involvement (83).

There have also been developments in laboratory techniques to aid identifying plastics within the environment. Digestion protocols have been developed to separate plastics from a range of environmental matrixes such as biota tissue, water, and sediments (84–86). However, techniques can have different plastic extraction efficiencies. Courtene-Jones et al. (87) tested a range of proteolytic digestive enzymes to establish optimum digestion efficacy of biological samples and assess the effects of enzymes on microplastics. In this research, they tested enzymes such as trypsin, papain, and collagenase. Trypsin yielded the greatest digestive efficacy based on weight reduction of biological samples (88% ± 2.52 SD) at the lowest concentration (0.3125%) with no observed impacts on microplastics. However, another study assessed organic matter digestion efficiency on plankton samples and microplastics weight, size, and polymer changes under different digestion techniques (88). A 2-step (KOH and $H_2O_2 + Fe^{2+}$) and 3-step (2-step and enzymes) digestion technique was assessed under different durations and temperature conditions but it was reported that any method applying high temperatures, aggressive reagents as acids, and prolonged digestions will damage microplastics.

Additionally, lab-based counting and chemical identification of plastics (especially microplastics and nanoplastics) can be time-consuming, especially when particles are numerous. There have also been developments in thermal desorption techniques such as pyrolysis gas chromatography/mass spectrometry; for example, Leslie et al. (89) measured plastic particle masses in blood per polymer type, although not the number of particles. To save resources, a subsample of particles is often selected, but as no standard subsampling protocols currently exist, methods vary widely and often lack evidence of representativeness, limiting conclusions and cross-study comparability. De Frond et al.'s (90) study used public data sets to determine best practices for subsampling >100 µm microparticles for chemical identification based on two research objectives: (*a*) quantifying the proportion of plastic, anthropogenic, and natural particles and (*b*) quantifying the diversity of material types. They report that particle selection at random provides a representative subsample with the lowest effort, but researchers must understand particle diversity within the environmental matrix in question to inform necessary sampling volume.

SOURCES

Understanding the specific sources of plastic debris is critical to help focus on major intervention points. Sources can generally be split into marine or land based. Marine-based sources typically include fishing, boating, and shipping. However, as major research efforts have primarily focused on land-based sources, there is less understanding on the specific marine-based sources and subsequent quantities, but they contribute much more directly to marine pollution since source and sink are geographically linked. Land-based sources include primary industry, litter, sewage, and stormwater. Land-based coastal pollution (within 50 km of coastlines) is considered to be the major source of marine plastic pollution, contributing approximately 9 million tons per year (18). However, the potential for impacts does not differentiate among sources.

As well as geographic origin, plastic sources can also be further defined by size category and product type. Macroplastic pollution (>20 mm) has been widely reported since the 1990s (91), and this issue has had increased public attention and is now covered by several international regulations. Macroplastic can enter the environment from many different products, but more than 40% of this amount is estimated to be for single-use applications, which can include plastic carrier bags, cutlery, straws, cups, and food packaging (92, 93). This creates a large amount of persistent plastic waste, and a proportion of this waste can enter the environment as litter. For example, Stanton et al. (69) conducted a detailed citizen science survey of anthropogenic litter across freshwater, terrestrial, and coastal environments of the United Kingdom. They reported that beverage items (defined as any item associated with beverages, including containers, lids, stirrers, and straws) and nonbeverage packaging represented 56% of anthropogenic litter, accounting for 33% and 22%, respectively. Following these, plastic fragments, cigarette items (packaging, filters, and butts), and expanded polystyrene were the only other categories to represent >5% of the anthropogenic litter recorded, at 9%, 6%, and 5%, respectively (69). Surveys that categorize plastic to the product level can aid source attribution and efforts to associate pathways of anthropogenic litter with key stakeholders.

There has also been focus on the specific sources of microplastic (<5 mm), such as microbeads, tire particles, road markings, and fragmentation from larger objects. Plastic microbeads were used over natural alternatives by the cosmetics industry, and a single bottle of facial scrub was found to contain more than 3 million plastic particles. These microbeads then get washed down the drain after use and then potentially travel through water treatment processes into aquatic environments (94). Likewise, tire road wear particles and road markings can be transported by rainwater into rivers and sewers, where they can pass through the water treatment process, or potentially to the ocean through the atmosphere (95, 96). Research into microplastic generation via fragmentation of larger objects reveals item age, weathering, and use are influential factors; for example, Napper et al. (97) tested a variety of ropes used in the maritime sector and reported that new and one-year-old rope released significantly fewer microplastic fragments (29 ± 3) and less microplastic mass (12 ± 1 μg) per meter hauled compared to ropes of two (720 ± 51, 247 ± 18 μg) or ten (767 ± 55, 1052 ± 75 μg) years of age.

Synthetic microfibers are the most commonly reported form of microplastics in the environment, from soil to aquatic systems (e.g., oceans, rivers, shorelines, and lakes) (21, 98). In 2017, approximately 60% of textile fibers produced globally were reported to be synthetic (e.g., polyester, nylon) (99), and more than 42 million tonnes of synthetic fibers are produced each year by the clothing industry (100). As such, it has recently been estimated that more than 6 million microfibers could be released from an average domestic 6 kg wash (101) or as a result of wearing clothes, with 400 microfibers per gram of fabric shed by items of clothing during just 20 minutes of normal activity (59).

Recently, the COVID-19 pandemic also showed how consumption trends can impact the different sources of litter within the environment. The pandemic resulted in increased consumption of single-use plastic items and an unprecedented surge of personal protective equipment (PPE), including face masks, disposable gloves, and disinfectant wipes. Widespread public use of PPE items resulted in increased pressure on municipalities to properly collect and dispose of PPE, but a proportion was found as debris in the environment (102). Research during the pandemic investigating the quantity of PPE as litter in Toronto (Canada) reported that the highest daily average densities of PPE debris were recorded in large and medium-sized grocery store parking lots and in the hospital district (0.00475 items/m^2, 0.00160 items/m^2, and 0.00133 items/m^2, respectively) (102). Additionally, the pandemic in many cases took precedence over many policies and initiatives related to mitigating plastic pollution; for example, in England, the much-announced ban on plastic straws and cotton buds was postponed for a minimum period of 6 months during the pandemic (103).

PLASTIC DEGRADATION

Even if emissions of larger items into each environment were to immediately stop, it is likely that we would still see an increase in the quantity of smaller debris pieces (such as microplastic and nanoplastic) as a consequence of the fragmentation of larger items that are already in the environment (104, 105). However, our understanding of fragmentation rates remains limited and requires better understanding (106, 107). Degradability of plastic is determined by its intrinsic properties (such as polymer type), but it is also strongly influenced by abiotic parameters (including temperature, moisture, and UV-radiation) as well as by biotic factors (such as the enzymes produced by the microorganisms colonizing the plastic surface) (108, 109). Only a few studies investigating the degradation of plastics have conducted research under natural or environmental conditions (110, 111). Immersing plastic in soil or compost, or incubation in a lake, a river, or the ocean, provides a realistic environment where plastic litter could end up. However, the complexity of environmental conditions such as pH value, temperature, or humidity, all of which cannot be well controlled and demand careful documentation, complicates field tests (112). Because degradation depends on both the material and the receiving environment, there are no widely applicable estimates for how long it takes for plastic to completely mineralize in the environment. Mineralization includes microbial conversion of all the organic constituents of a material to carbon dioxide, new microbial biomass, and mineral salts under oxic conditions or to carbon dioxide, methane, new microbial biomass, and mineral salts under anoxic conditions (113).

Most studies have focused on the degradation of plastics in marine environments. Plastics exposed on the surface or in the photic zone (the top 200 m of water in the water column) of seawater can be photodegraded by ultraviolet light and can result in weight loss, changes in appearance and texture, deterioration in mechanical properties, signs of oxidation, and alteration of physicochemical properties (114, 115). While photodegradation is mainly responsible for the initial degradation of plastics floating on the surface of seawater, for some polymers biodegradation by microorganisms may also be a cause of plastic degradation in seawater in the aphotic zone (this zone starts at 2,000 m deep in the water column and extends down to the ocean floor (116)).

Degradation rates will vary according to the properties of the receiving environment and will be influenced by temperature, light, pH, humidity, etc. Research in terrestrial environments investigating the degradation of PE films and microbial community composition reported that plastic degradation can be affected by different conditions (soil layer, time, and plants) (117). The freshwater environment also differs in several aspects, including sunlight spectrum and intensity, water physicochemical properties, and biological characteristics. However, compared to the marine environment, fewer studies have focused on understanding the degradation in different environmental conditions (21, 118).

One approach intended to tackle the problem has been the development of plastic formulations said to deteriorate faster and/or have fewer impacts on the environment because of their shorter persistence. For example, many agricultural plastic films, which provide multiple benefits for food production, are now using biodegradable plastics due to the complexity of removal and the lack of alternative disposal options (119). However, Napper & Thompson (111) showed that products labeled as biodegradable can persist in the soil and the marine environment for more than 3 years. Compostable plastic tested in the same experiment completely disappeared from test rigs in the marine environment within a 3-month period, but the same plastic remained intact in soil after 3 years. Therefore, it is not clear that such plastic formulations provide sufficiently advanced rates of deterioration to be advantageous in the context of reducing marine litter. Many of the formulations described as biodegradable or compostable need to be disposed of in an industrial composter, at temperatures greater than those reached in natural environments; without this, their degradation properties may well be similar to conventional plastic. In addition, formulations that are designed to be less durable may compromise recyclability since they decrease the durability of the recyclate. Therefore, statements about the degradation of plastic products should be clearly linked to appropriate standards, made in conjunction with statements on the receiving environment (air, soil, water) and timescale to which those claims relate. These standards would need to be appropriate for the wide variability of natural environmental conditions (e.g., temperature/pH/light) and have appropriate timescales to ensure items are deteriorating sufficiently rapidly to make a difference, compared to conventional plastics, and not release any potentially harmful degradation products (chemicals or fragments).

The term bioplastic is also often misused and has created some confusion. Bio-based polymers are composed or derived in whole or in part of biological products issued from the biomass (including plant, animal, and marine or forestry materials) (120). However, a bio-based polymer is neither guaranteed to be biodegradable in the natural environment nor any more “environmentally friendly” than a conventional polymer.

IMPACTS

The accumulation of plastic debris (macro-, micro-, and nanoplastics) in the environment is associated with a range of impacts. Impacts can largely be split into three main categories: (*a*) impacts to fauna and flora within the environment, (*b*) economic consequences, and (*c*) impacts to health and well-being (**Table 1**). There are, however, many interrelated themes within these categories.

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In terms of fauna and flora, the effects depend on many factors, including size, shape, polymer type, and, if being ingested, the feeding type of the exposed organism (125, 127). A well reported and visible effect of macroplastic pollution on marine organisms is entanglement in marine debris, often in discarded or lost fishing gear and ropes (121, 123). When entangled, organisms can be hindered in their ability to move, feed, and breathe. Within the marine environment, plastics have been used as a nest material (128), as a floating dispersal vector (151), and as refuges/shelters for several marine species (133). Blettler et al. (152) provide evidence that freshwater and terrestrial species are also negatively affected by the same type of plastic encounters described for marine species.

In addition, many organisms consume plastic indiscriminately or mistake it for food and ingest it. More than 1,565 wild species throughout the environment are currently known to ingest plastic (153). Huerta Lwanga et al. (154) examined the transfer of plastic to terrestrial species, assessing micro- and macroplastic in soil, earthworm casts, chicken feces, crops, and gizzards (used for human consumption). Microplastic concentrations increased from soil (0.87 ± 1.9 particles g^{-1}), to earthworm casts (14.8 ± 28.8 particles g^{-1}), to chicken feces (129.8 ± 82.3 particles g^{-1}). Chicken gizzards contained 10.2 ± 13.8 microplastic particles, whereas no microplastic was found in crops. An average of 45.82 ± 42.6 macroplastic particles were found per gizzard and 11 ± 15.3 macroplastic particles per crop.

Ingestion of plastic by wildlife has been shown to lead to physical or chemical impacts. Physical impacts may include blockages in the digestive tract when plastic is consumed by animals (126), which can lead to false satiation. Plastics may also serve as a delivery system for potentially toxic pollutants, including some plastic additives incorporated during the manufacturing process (e.g., plasticizers) or chemicals that have sorbed to plastic from the surrounding environment (e.g., heavy metals) (130, 155). For example, some microplastics have been shown to contain additives that have the potential to act as reproductive toxins and carcinogens (156).

Additionally, such chemicals could potentially transfer up the food chain through ingestion at multiple trophic levels, and the implications for food webs are not yet fully understood (157). Laboratory exposure has shown that leaching of plastic additives can have toxicological effects on barnacles, anemones, and Japanese medaka (135, 158–160). Exposure has been linked with reduced body size (124) and nutrition levels (129) as well as altered blood chemistry (131). Nanoplastics are also an emerging focus of concern. The first study to quantify the uptake of nanoparticles at environmentally relevant conditions found that after six hours of exposure in the laboratory, billions of particles measuring 250 nm (~0.00025 mm) had accumulated within a scallop’s intestines (161).

Microplastics have also been observed in human stools (146, 148), human placenta (149), human breast milk (150), in vitro human gut microbiota, and Caco-2 human cells (147, 162), leading to considerable discussion on the extent to which microplastics and nanoplastic might affect human health. Furthermore, bisphenol A (BPA), an additive used in the manufacture of plastic materials, has been found in human tissues and urine (163). Epidemiological studies suggest there is link between BPA exposure in humans and multiple adverse endocrine consequences, including not only male and female reproductive functions but also alterations to thyroid hormones, immune function, disruption of glucose homeostasis (diabetes), cardiovascular disease, and obesity (164).

The sheer accumulation of plastic and its presence has already had negative physical effects in some ecosystems. To set the scale of the problem, by mass, it is estimated that there could be twice as much plastic in the world (8 Gt) than animal life (4 Gt) (164, 165). A wide range of effects have been demonstrated; to a greater or lesser degree, plastic has been shown to increase melting rates of snow and ice (138), increase soil temperature and reduce habitat suitability (166), increase disease likelihood in coral reefs (134), facilitate the transport of invasive species across habitats (151), and deposit in sediments, leading to potential impacts on the animals that live and forage in the benthos (136). Many of these impacts have been identified as being "poorly reversible," due to the difficulty of reducing plastic emissions (137). There is also evidence that even small quantities of litter on beaches may have a negative effect on human well-being; a study with an experimental laboratory approach using systematically varied photographic stimuli showed that marine litter can undermine the psychological benefits that the coast ordinarily provides (145).

However, some studies reporting the ecological and environmental risks of microplastics have been questioned because of the unrealistic concentrations of plastic and characteristics used in the laboratory experiments with those observed from the field. For example, studies have shown that fibers are the dominant particle type across multiple environmental matrices globally (31, 167); synthetic microfibers accounted for 50–100% of microplastics from samples extracted along a longitudinal gradient traversing the subtropical gyre in the North Atlantic Ocean (168) and were the most abundant microplastics found in urban (70%) and industrial (55%) soils in Ahvaz metropolis (Iran) (169). However, these are infrequently used in laboratory testing for particle behavior or toxicity. Additionally, the longevity of plastics means that ecosystem exposure will be long term, yet the majority of exposure studies to date have been short term (typically hours, days, or weeks) (170). Therefore, when considering ecological hazards, future research should strive not to establish toxicity thresholds but to determine the effects of plastics and their additives under realistic scenarios and timescales by using environmentally representative particle types, concentrations, and chronic exposures (171, 172). It is not possible to spend indefinite amounts of time and money investigating all possible permutations of plastic exposure and hazards.

The substantial quantities of plastics that are entering the environment daily can also present a range of negative economic consequences. Cost implications can occur with impacts on navigation, agriculture, aquaculture, tourism, and fisheries (143). Of particular note, ecosystem services and natural capital values can also be impacted. These provide a wealth of services (the benefits people obtain from nature), including food provision for billions of people, carbon storage, waste detoxification, and cultural benefits like recreational opportunities and spiritual enhancement (139, 142). Based on these impacts, Beaumont et al. (173) estimated that the economic cost of marine plastic alone, as related to marine natural capital, was conservatively conjectured at between $3,300 and $33,000 per tonne of marine plastic per year (based on 2011 ecosystem service values and marine plastic stocks). McIlgorm et al. (144) then predicted that damage from marine litter (of which the majority is plastic) globally was $18.3 billion per year in 2015, equating to $21.3 billion in 2020 and is an "avoidable cost." The full economic cost to the environment is likely to be far greater as this value includes only marine estimates.

SOLUTIONS

Plastics make numerous positive contributions to our society. If used responsibly, plastics can potentially reduce our human footprint on the planet, improve standard of living, and alleviate suffering. However, it is equally clear that plastic debris is accumulating at an unprecedented rate across the natural environment and in managed waste streams. As such, solutions to mitigate accumulation are increasingly being proposed. Research by Lau et al. (4) suggests that although no silver bullet solution exists for plastic pollution, 78% of the plastic pollution problem could be solved by 2040 using combinations of approaches including reduce, reuse, and recycle. However, granular evidence on specific interventions, their efficacy, and the trade-offs among them is lacking (174).

Using our current knowledge, solutions on plastic litter need to include coordinated actions among industry, policy, and the public, at levels from local to worldwide. This is because plastic debris does not recognize international boundaries. The use of international agreements can then filter down to national levels; for example, the UN Development Goals aim for nations to "prevent and significantly reduce marine pollution" by 2025 (175). The European Union (EU) also has a Circular Economy Action Plan that implements a waste hierarchy in which prevention, reuse, recycling, and energy recovery are favored over landfill in this respective order (176).

The waste hierarchy (**Figure 1**) involves utilizing more sustainable production and consumption patterns that will ultimately lead to waste reduction, for example, designing products for reuse/recycling and also avoiding unnecessary plastics use. However, the most preferable option is to prevent waste from being generated in the first place. These reduction strategies can be broadly partitioned into upstream (preconsumption, reducing demand) and downstream (postconsumption, such as collection and recycling measures) solutions. There can be issues because even in highly developed countries with robust waste management infrastructure, there are unnecessary obstacles, including the lack of collection points, contamination of recycling feedstock, and the limited marketability of some recycled material (70, 178).

Figure 1 The waste hierarchy. A priority order for managing waste materials based on their environmental impacts. Figure adapted with permission from the European Commission (177).

Other management strategies and policies can include the use of targets, taxes, education, and bans. Governments globally banning microbeads in cosmetics is an example of such legislation. Furthermore, taxes introduced on plastic items have already been shown to be instrumental in changing consumer behavior with regard to plastic. A fifteen euro cent tax on plastic bags in Ireland led to a 90% reduction of plastic bag usage in the early 2000s (179). However, based on the levels of concern and the scale of plastic debris throughout the environment, overall it would appear that the current measures used are insufficient.

Solutions and implementation also depend strongly on the respective country and its cultures and infrastructure. Focusing on the 35 top-ranked countries for mass of mismanaged plastic waste, Jambeck et al. (83, 180) suggested that to achieve a 75% reduction in the mass of this waste, waste management would have to be improved by 85%. This strategy would require time and substantial infrastructure investment, primarily in low- and middle-income countries (181). Within these countries, the main focus needs to be on improving solid waste collection and management. However, open dumping or burning is reported to be common in African and Asian countries (182, 183), whereas studies from Europe usually rate plastic as one of the more commonly recycled materials (184).

There are further difficulties within this. Some relatively developed nations export a significant proportion of waste to developing nations that may lack sufficient capacity to appropriately manage this waste. For instance, one recent report indicated the United States produced an estimated 42 Mt of plastic waste in 2016, of which 0.14 to 0.41 Mt was allegedly illegally dumped into the environment (land and water) and another 0.15 to 99 Mt was exported to other nations like South Africa, Indonesia, and Mexico, where it was insufficiently recycled (either burnt or discarded in open landfill sites) (185). Additionally, in 2021 exports of waste from the EU to non-EU countries reached 35 million tons, an increase of 77% since 2004. Türkiye was found to be the largest destination for waste exported from the EU, with a volume of approximately 16 million tons in 2021 (186). Reports of technologically and economically advanced countries such as the United States and others in Europe highlight one of the key challenges facing global efforts to mitigate plastic pollution, i.e., the tendency to pass the responsibility for their waste on to poorer nations, who are less equipped to manage that waste. Socioeconomic differences among nations will also play a role; a study in India suggested that households with lower income reused waste themselves, whereas households with higher income gave it away for reuse and recycling (187).

Additionally, a large focus on solutions has been in technological innovations. To track such developments, a study by Schmaltz et al. (189) created a comprehensive inventory of technologies currently used or in development to prevent the leakage of plastic pollution or collect existing plastic pollution. They report that the majority of available technologies are collection technologies (38 inventions), with fewer technologies focused on preventing plastic leakage (14 inventions).

Marine debris removal technologies have focused on collecting macroplastic waste (such as plastic bottles) from aquatic environments because these larger items are more accessible and have potential value in recycling streams. For example, funded mainly by donations, the Ocean Cleanup Array has been promoted as a solution for extracting plastics accumulating in the ocean gyres by harnessing ocean currents (190). The device could potentially collect 7.25 million tons of plastic debris from the ocean (191). Since deployment in August 2021, the organization has collected 101,353 kg of plastic over 45 extractions, from an area of more than 3,000 km^2 (comparable to the size of Luxembourg) (192). After collection, they aim to recycle the majority of plastic to pass onto partners that process the plastic to make durable new products (193). Another collection technology, Mr. Trash Wheel in Baltimore, Maryland (USA), has reportedly collected 2,004 tons of waste over the course of approximately 2.5 years (https://www.mrtrashwheel.com/).

However, the quantity of plastic entering the ocean far outweighs the quantity that could currently be collected; a study evaluated the efficiency of solutions regarding ocean cleanup devices and river barriers using modeling tools and reported that it would take 100 years to remove 5% of ocean plastics when using ocean cleanup devices alone (195). Although these efforts to collect plastic pollution are laudable, their current capacity and implementation are limited; there are also concerns that the efficacy of cleanup devices should be fully tested before they are marketed. For example, Parker-Jurd et al. (196) tested the performance of a Seabin, a fixed-point cleaning device, in a tidal marina in the South West of the United Kingdom. It was reported that the Seabin captured on average 58 items of litter/day, reflecting the proportions of various litter items present in the marina. However, the device also captured on average 13 marine organisms a day, half of which were deceased upon retrieval. Therefore, the rate of litter capture by the Seabin was concluded to be inferior to manual cleaning efforts. They further report that excessive reliance on technological innovation and advancements in solving environmental problems [also described as techno-optimism (197)] can undermine motivation for mitigating actions (198). At an extreme, techno-optimism may reduce a personal sense of responsibility for waste and litter by perpetuating the illusion that technology is taking care of the problem, and littering could be seen as more acceptable in the presence of cleanup devices.

Technologies focused on preventing plastic leakage typically focus on a specific source. For example, Napper et al.'s (199) study compared the efficacy of six different devices designed to capture microfibers released from clothing during the washing cycle. These devices varied from prototypes to commercially available products and were designed to be either placed inside the washing machine drum during the washing cycle or fitted externally to filter the effluent wastewater discharge. Napper et al. reported that the devices ranged in efficiency (21–78%) in stopping microfibers entering the wastewater. This further highlights that emerging technologies may have various efficiency rates or additional issues.

Clearly, we should not become reliant on cleanup technology to fix the problem; there is no single solution that fixes all. The issue of microfibers from wear and washing of clothing demonstrates this. As mentioned, devices fitted to washing machines have been evidenced to reduce fiber emissions in washing effluent up to 78% (199). However, these are currently not widely utilized or retrofitted to domestic washing machines by manufacturers. Furthermore, these filters would not address emissions of microfibers to the atmosphere as a consequence of wearing the clothes. This is evidenced from a recent study by Napper et al. (200), which aimed to quantify and compare the quantities of microfiber entering the marine environment via two major pathways: wastewater discharge and atmospheric deposition. Fibers originating from the atmosphere were deposited at an average rate of 81.6 fibers m^2 d^{-1} across urban and rural areas. Treated wastewater effluent contained on average 0.03 synthetic fibers L^{-1}, and they estimated that ~20,000–500,000 microfibers could be discharged per day from the wastewater treatment plants studied. Subsequently, atmospheric deposition of synthetic microfibers appeared to be the dominant pathway but typically receives less attention. In many locations, once microplastics have been captured in wastewater treatment the resultant sludge is returned to the land as an enrichment—hence the microplastics that were captured are released back to the environment. Yet there is very good evidence that changes in fabric design could be a very effective overarching mitigation strategy, with divergences of approximately 80% in the rate of fiber release between similar garments. Changes in design will be critical for reducing emissions during all use phases: wearing, washing, and tumble drying (200).

Some have advocated replacing synthetic textiles with natural counterparts, but these are typically more expensive and the impact of nonsynthetic microfibers accumulating in the environment is also currently unknown (201). For example, a recent study tested behavioral and growth impacts of natural cotton and synthetic (polyester and PP) microfiber (80–120 µm) in two estuarine indicator species (mysid shrimp and silversides) across a salinity gradient; the natural microfibers were identified as least toxic when compared to the other two synthetic microfiber types, but they still caused adverse responses in terms of growth in mysids and altered behavior in both taxa (202).

CONCLUSIONS

Over the past decade, there has been substantial growth in plastic debris research, which has largely focused on clarifying the variety of sources, distribution, accumulation, and impacts of plastic in the environment. Although there is good understanding of the prevalence of plastic debris in the environment and potential impacts, there is still less clarity on the relative importance of various environmental pathways and sources. This presents a major barrier to implementing solutions. However, there is a firm understanding that the rate of plastic pollution entering the environment far exceeds the rate of cleanup and or complete mineralization. Therefore, the priority must be to focus on waste minimization and preventing debris entering the environment in the first place. As we move toward solutions, it is imperative these are fully evaluated in advance of their use in order to understand their efficiency, unintended consequences, and potential trade-offs (174).

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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Table 1 Impacts of plastic debris

Types of impact	Impacts	References
Impacts to fauna, flora within the environment	Entanglement: Organisms can be hindered in their ability to move, feed, and breathe.	Laist (121), Blettler & Mitchell (122)
	Ingestion: Physical impacts may include blockages in the digestive tract when plastic is consumed by animals, which can lead to false satiation.	Baulch & Perry (123), Lavers et al. (124), Ogonowski et al. (125), Ryan (126), Scherer et al. (127), O'Hanlon et al. (128), Puskic et al. (129)
	Chemical: Impacts from plastics may serve as a delivery system for potentially toxic pollutants. Such chemicals could potentially bioaccumulate up the food chain through ingestion at multiple trophic levels. Exposure has been linked to reduced body size and nutrition levels as well as altered blood chemistry.	Gallo et al. (130), Lavers et al. (131)
	Other impacts: Other impacts can include increased melting rates of polar snow and ice, increased soil temperature and reduced habitat suitability, increased disease likelihood in coral reefs, facilitation in the	Kiessling et al. (132), de Carvalho-Souza et al. (133), Lamb et al. (134), Turner (135), Brandon et al. (136), MacLeod et al. (137), Zhang et al. (138)

	transport of invasive species across habitats, and deposition in sediments, leading to potential impacts on the animals that live and forage in the benthos	
Economic consequences	Biodiversity: loss of biodiversity globally and related ecosystem services	Worm et al. (139), Naeem et al. (140)
	Reduction in natural capital values: less control of flooding, climate regulation, and surface water provision	Ofiara & Seneca (141)
	Ecosystem services: impacts to food provision, waste detoxification, and cultural benefits including recreational opportunities	Liquete et al. (142), Beaumont et al. (143)
	Business: impacts to agriculture, aquaculture, tourism, and fisheries	McIlgorm et al. (144)
Impacts to health and well-being	Human well-being: Litter can undermine the psychological benefits that the environment provides, potential loss of food security, livelihoods, income, and good health.	Wyles et al. (145)
	Health: Plastics have been observed in human stools, human placenta, human breast milk, in vitro human gut microbiota, and Caco-2 human cells. There is good evidence	Schwabl et al. (146), Fournier et al. (147), Ibrahim et al. (148), Ragusa et al. (149, 150)

	that chemicals used in plastics production can be harmful to human health and that chronic exposure in production and unregulated waste management practices as open burning can be very harmful. However, the extent to which plastic litter in the environment presents toxicological hazards is less clear.	