REVIEW SUMMARY

MICROPLASTICS

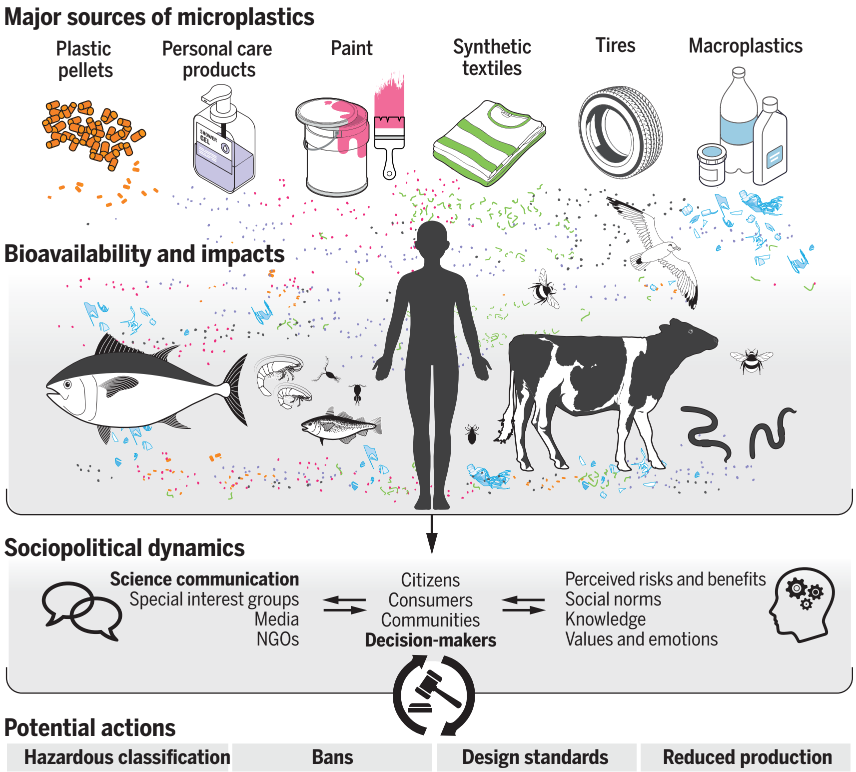
Twenty years of microplastic pollution research—what have we learned?

Richard C. Thompson*, Winnie Courtene-Jones, Julien Boucher, Sabine Pahl, Karen Raubenheimer, Albert A. Koelmans

BACKGROUND: The term microplastic was first used to describe microscopic fragments of plastic debris (~20 μm in diameter) in a publication in 2004. On the basis of this paper and earlier work, it was evident that small fragments of various common plastics—including acrylic, polyamine (nylon), polypropylene, polyester, polyethylene, and polystyrene—were present in coastal environments around the United Kingdom and along the eastern seaboard of the United States and that their abundance had increased substantially since the 1960s. There was evidence that microplastics were bioavailable to invertebrates and fish but only speculation on the key sources and the potential for harmful effects.

ADVANCES: Microplastics, now widely defined as pieces ≤5 mm in size, are recognized as a highly diverse set of globally important contaminants. Multiple sources are now confirmed, including primary microplastics in cosmetics and paint as well as the pellets and flakes used to make plastic products, along with secondary microplastics generated by the abrasion of larger items during use, including textiles and tires, and the fragmentation of larger debris in the environment. Microplastics can be redistributed by wind and water and have since been reported in diverse locations, from the sea surface to deep-sea sediments, from farmland to our highest mountains, and in sea ice, lakes, and rivers. They have been detected in 1300 aquatic and terrestrial species, from invertebrates at the base of the food web to apex predators, with evidence of impacts at all levels of biological organization, from cellular to ecosystem. Microplastics are pervasive in the food we eat, the water we drink, and the air we breathe. They have been detected in multiple tissues and organs of the human body, with emerging evidence of potential effects.

This rapidly unfolding scientific evidence, together with individual, social, and societal drivers of change, is leading to policy outcomes that include national-level regulations, such as the prohibition of microplastics in cosmetics by multiple countries and a mandate in France requiring that filters be installed in washing machines to intercept microfibers, as well as multinational policies, including the EU Marine Strategy Framework Directive and the REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) legislation on intentionally added microplastics.



Microplastic pollution: Sources, impacts, and actions. Twenty years of research focused on microplastic pollution has identified their multiple sources, wide-scale environmental distribution, bioavailability, and impacts. This evidence, together with the associated sociopolitical dynamics, has started to drive actions on a global scale. NGOs, nongovernmental organizations.

ILLUSTRATION: J. BEADON

OUTLOOK: Emissions of microplastics to the environment are estimated to be between 10 and 40 million tonnes per year, and under business-as-usual scenarios, this amount could double by 2040. Even if it were possible to immediately halt emissions, quantities would continue to increase because of the fragmentation of legacy items. Modeling predictions indicate the potential for wide-scale environmental harm within 70 to 100 years, but detailed risk assessments are limited because exposure and effect data are incomplete. This is especially true for human health effects. Although we anticipate greater clarity over the next few years, public risk perception is also a key driver of actions and is often influenced by a wider range of factors than objective risk assessment; for example, German consumers recently rated microplastics in food as being their top environmental health concern.

Can we afford the externalized costs of microplastics that are already understood, and if not, which criteria should guide interventions and what is essential, in the context of societal needs and desires? A whole-system approach from extraction to remediation will be key to creating material flows that satisfy human needs with minimal environmental impact. Twenty years of science defining microplastic pollution now brings a tangible opportunity for international action as part of the United Nations Environment Programme draft global plastics treaty. Together with reductions in primary polymer production, measures will be needed to reduce emissions and pollution along the entire life cycle of plastics, including dedicated provisions on microplastics. However, there is a high risk of unintended consequences if interventions are implemented without appropriate evaluation. ■

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Twenty years of microplastic pollution research—what have we learned?

Richard C. Thompson[1]*, Winnie Courtene-Jones[1], Julien Boucher[2], Sabine Pahl[3], Karen Raubenheimer[4], Albert A. Koelmans[5]

Twenty years after the first publication that used the term microplastic, we review current understanding, refine definitions, and consider future prospects. Microplastics arise from multiple sources, including tires, textiles, cosmetics, paint, and the fragmentation of larger items. They are widely distributed throughout the natural environment, with evidence of harm at multiple levels of biological organization. They are pervasive in food and drink and have been detected throughout the human body, with emerging evidence of negative effects. Environmental contamination could double by 2040, and wide-scale harm has been predicted. Public concern is increasing, and diverse measures to address microplastic pollution are being considered in international negotiations. Clear evidence on the efficacy of potential solutions is now needed to address the issue and to minimize the risks of unintended consequences.

Reports of large items of plastic debris in the environment date back to the 1960s [see reviews (1, 2)]. In the 1970s, sampling focused on marine plankton, and neuston communities revealed the presence of small plastic fragments and fibers in net tows from locations in the North Sea, UK (3); Sargasso Sea (4); Northwestern Atlantic (5, 6); and South Africa (7). The term microplastic was first used to describe microscopic fragments of plastic debris (~20 μm in diameter) in a publication in 2004 (8). This paper, described as marking the beginning of the field of microplastics research (9), demonstrated that small fragments of various common plastics, including acrylic, polyamine (nylon), polypropylene, polyester, polyethylene, and polystyrene, were present in coastal environments around the UK and that their abundance had increased significantly since the 1960s.

Microplastics are now widely defined as solid plastic particles ≤5 mm in size that are composed of polymers, together with functional additives as well as other intentionally and unintentionally added chemicals (10). Although it does not follow the SI convention of units (Fig. 1E), this size definition resulted from an early policy meeting hosted by the National Oceanic and Atmospheric Administration (NOAA) in Tacoma, WA, USA (11), which proposed this upper size bound (Fig. 1E) because of evidence that particles up to 5 mm could readily be ingested by organisms and growing concerns that they might present different risks than larger items, which were already known to cause harm. The European Union (EU) subsequently adopted this upper bound of 5 mm in its Marine Strategy Framework Directive (12). In most studies, the lower size bound is typically constrained by methodological limitations to the minimum size of particles that are possible to isolate and identify from complex environmental mixtures (see section Methodological advances). At sizes smaller than >1 μm, we move from micro to nano, and although nano-sized plastic particles have almost certainly accumulated, they are presently too small to individually identify from environmental samples.

Subcategories of microplastic linked to their sources have since been described, including the terms primary and secondary microplastics, but this terminology has not been used consistently (10). This is especially the case for particles and fibers generated by wear, with multiple publications considering these to be primary microplastics [e.g., (13–15)] and the others considering them as secondary microplastics [e.g., (10, 16, 17)]. To minimize potential ambiguity in new legislation, we propose a universal scheme of definitions (Fig. 1A) that incorporates recently described sources, resulting in three categories of primary microplastics, which are manufactured ≤5 mm, and three categories of secondary microplastics, which all originate from items that are >5 mm at manufacture, either as a consequence of wear during use, from fragmentation in waste management, or from fragmentation in the environment. Other terms aligned with primary and secondary that have been used in policy contexts, including draft text for the United Nations Environment Programme (UNEP) legally binding international treaty on plastic pollution, which is presently under negotiation (hereinafter referred to as the "global plastics treaty"), include "intentionally added microplastics" and microplastics that are "unintentionally" released or generated by degradation (Fig. 1A).

Sources, transport, distribution, and environmental concentrations of microplastics

Over the past two decades, hundreds of papers have specifically focused on the environmental accumulation of microplastics, including on shorelines (18); in the deep sea (19); in the water column (20); in sea ice (21); in organisms across biological taxa, from invertebrates at the base of the food web to apex predators (22, 23); and, more recently, in rivers, lakes, and streams (24, 25); in soils (26, 27); near the summit of Mount Everest (28); and in the atmosphere (29, 30). It is now clear that microplastics contaminate multiple environments on a global scale (Fig. 2C). Initial studies identified several key sources, including textile fibers (Fig. 1D) (3, 8), cosmetic cleaning products (Fig. 1B) (31), spillage of preproduction pellets (based on the <5 mm definition) (32, 33), and fragmentation of larger items (8), whereas sources such as paints, tire abrasion (Figs. 1C and 2A), construction, and preproduction flakes and powders have since been added (13, 15, 16, 34). Fragmentation of larger items in the environment appears to be the largest source, but in all cases, the underlying drivers are human activities (see section Human decisions and actions as causes and solutions of microplastic pollution). Emerging sources include plastic-coated fertilizers and mulch films used in agriculture (35), degradation of rope and netting in the maritime sector, mechanical recycling (36), and infill in sports pitches (37).

During use, the durability of plastic items is an important attribute, but resistance to degradation, at end of life, can also result in extensive accumulation of plastics in waste streams and the environment. Degradation and biodegradation are both systems properties that are influenced by the plastic material and its receiving environment, with exposure to ultraviolet light, heat, humidity, and aerobic conditions generally increasing chemical deterioration and wind or wave energy leading to fragmentation. However, substantial reductions in molecular weight are required before mineralization can occur [see (38) for reviews]. The rate at which macroplastics fragment into microplastics is not known, and neither are the extent to which microplastics potentially fragment into nanoplastics or the timescales required for plastics to be mineralized. Greater understanding of these transformation rates would be invaluable to risk assessment (see sections Ecological impacts and risk and Understanding the risks

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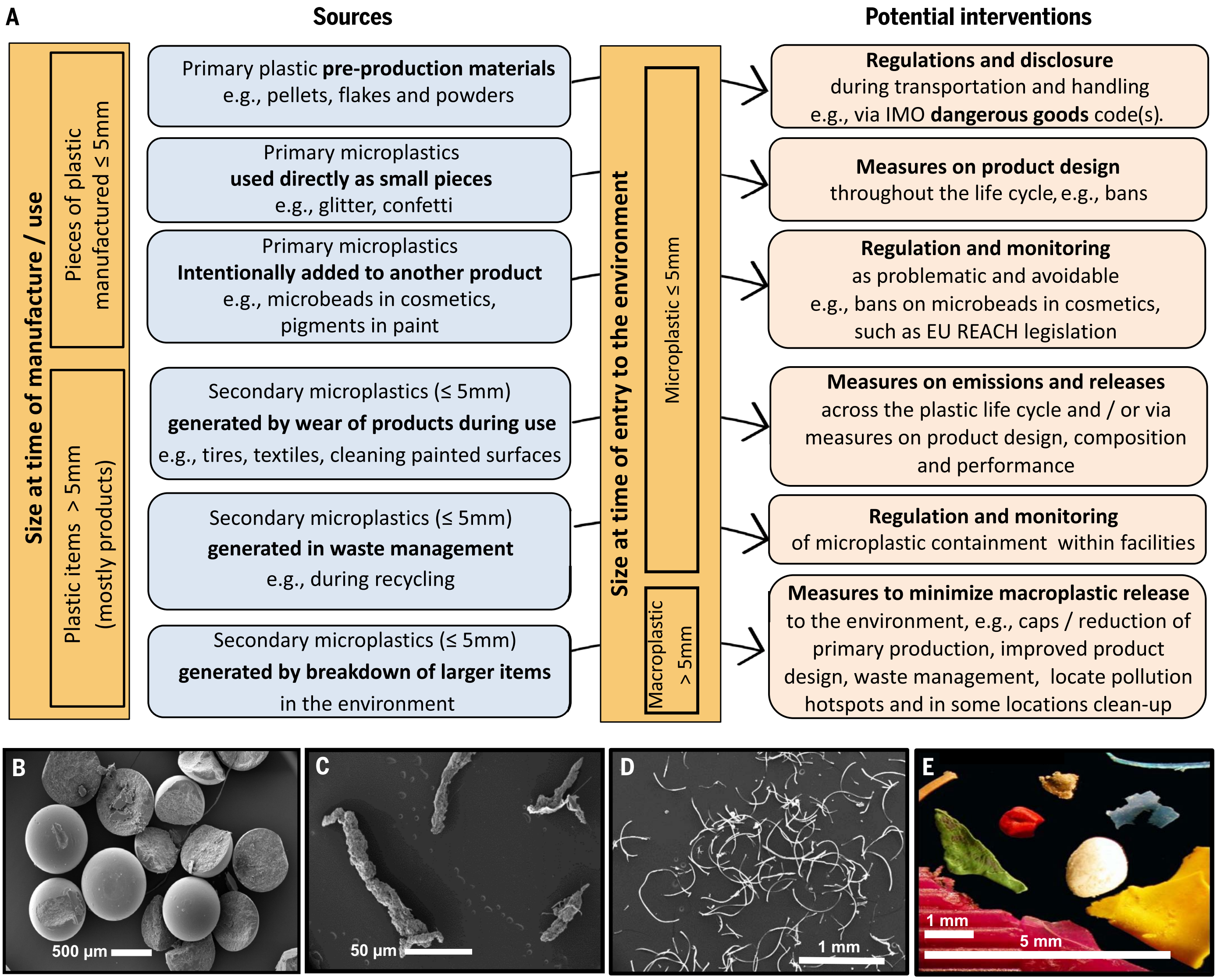


Fig. 1. Categories and sources of microplastic. (**A**) Scheme outlining our proposed nomenclature for microplastic categorization based on origin and size, together with potential interventions. (**B** to **E**) Electron microscopy images and a photo of various categories of microplastics: (i) microbeads from cosmetics (B), an example of primary microplastics; (ii) particles from vehicle tires (C) and fibers released from textiles (D), both of which are secondary microplastics generated by wear; and (iii) microplastics generated by fragmentation in the environment (E). Scale bars in (E) relate to the SI definition of micro (<1 mm) and the size definition for microplastics (≤5 mm) that have been adopted by policy-makers in the United States [NOAA (*11*)] and the EU. [Credits: Browne Plymouth Electron Microscopy Centre [(B) to (D)]; M. A. Browne (E)]

of microplastics to human health); however, the rate of mineralization would appear to be miniscule compared with the rate at which plastics are accumulating in the environment. Hence, it has been suggested that, with the exception of material that has been incinerated, all of the conventional plastic ever made is still present on the planet in a form that is too large to be biodegraded (*39*). Manufacturing plastics with enhanced rates of degradation has been promoted as a potential solution; however, incomplete degradation of such plastics has long been highlighted as a further potential source of microplastics. A recent expert group review concluded that although biodegradable plastics could bring benefits in very specific applications, for example, in agriculture or fisheries or in closed-loop systems, they do not offer solutions to the issue of littering or leakage from waste management streams and pose additional risks if biodegradable plastics end up in recycling waste streams (*40*).

Several recent studies have estimated the relative contributions of various sources of microplastics to the marine environment (Table 1 and Fig. 2B), including studies in Nordic countries (*41*, *42*) and the International Union for Conservation of Nature (IUCN)'s 2020 global assessment, which estimates a combined total of between 0.8 million and 3 million tonnes (Mt) per year (*13*). Although rates of fragmentation have not yet been derived, we also highlight the importance of macroplastics as a source of microplastics to the marine environment by illustrating the annual leakage of macroplastics to the ocean as a proxy (Fig. 2B; 7.6 Mt/year) (*43*, *44*). In addition, a recent report suggests that plastic leakage into terrestrial environments could be 3 to 10 times greater than that to the marine environment, resulting in a total of around 10 to 40 Mt of annual leakage to the environment (*45*). As understanding of potential sources increased, an apparent discrepancy emerged because the quantities of plastics entering the environment appeared to far exceed empirically grounded modeling extrapolations of quantities in the environment, which was highlighted in an article on "the missing plastic" (46, 47). Together with recent investigations into the amount of plastic present as smaller-size fractions (≥10 μm), which are harder to detect (48), recent studies have resolved this by quantifying microplastics in locations that had previously been overlooked, such as those suspended in the water column.

Points of entry into the environment include direct release into the air, for example, as fibers from textiles (49) or dust from tire abrasion (50); discharge to aquatic habitats as runoff from roads and sewage systems (51); direct introduction into agricultural soils, such as through the spreading of contaminated sewage sludge (52); and indirect sources that result from fragmentation in the environment. Once in the environment, microplastics can travel far from their point of entry (Fig. 2C) and are not constrained by national boundaries, which highlights the importance of actions at a global level (53) (see section Regulatory options to address microplastics). Rivers are recognized as major pathways that connect sources inland with the marine environment; the redistribution of finer airborne microplastic by wind is likely to be another major pathway leading, for example, to accumulation in remote regions (50), but its importance is not yet fully understood. In aquatic environments, microplastic particles are transported, deposited, and resuspended by water movement by the same processes as natural particulates. Hence, unlike dissolved contaminants, which become diluted as they disperse, there is the potential for microplastic particles to accumulate in low-energy locations, including in relatively remote areas such as the deep sea (19) or the Arctic (54). Although our understanding of the transport of microplastics can be informed by studies of natural particulates, the sheer diversity of microplastic shapes, sizes, and densities introduces distinctive differences compared with natural particulates and makes extrapolation challenging (55).

As new sources, pathways, and hotspots of environmental contamination are identified, it is important to emphasize that although each new study influences the relative importance of contributions among sources, the absolute quantities in the environment simply increase. For example, the importance of tire-wear particles only emerged around 2015, but this did not diminish the numerical abundance of other sources, such as fibers and pellets, that were already well documented at that time. Given the multiple sources, pathways, and broad environmental distribution of microplastics, addressing them at their source is imperative. To underscore the urgency, forecasting models indicate that, under business-as-usual scenarios, microplastic leakage to the environment could increase by 1.5 to 2.5 times by 2040 (44). Even if it were possible to halt all new releases of plastic to the environment, the quantity of microplastics would continue to increase over the foreseeable future because of the fragmentation of larger plastic items that are already present. The overarching message is clear—environmental concentrations and exposure of biota and humans to microplastics are set to increase.

Ecological impacts and risks

The bioavailability of microplastics to invertebrate filter feeders, deposit feeders, and detritivores, as well as to birds and fish, has been recognized for some time and is important because of the potential for plastics to adsorb, transport, and release chemicals and the potential for particle toxicity (56, 57). Evidence of microplastic accumulation across multiple ecosystems (see section Sources, transport, distribution, and environmental concentrations of microplastics) has been mirrored by numerous reports of microplastic ingestion in natural populations (38, 58) and the potential for transfer along food chains (Fig. 3). The relationship between microplastic type and abundance with ingestion is multifaceted (24, 59, 60). As plastics fragment into smaller and smaller pieces, their sheer quantity leads to increased availability to a wide range of organisms, from invertebrates at the base of the food chain to apex predators (Fig. 3), some of which mistake these particles for food (61, 62). The diversity in size, shape, color, and chemical composition of microplastics, together with surface colonization by microorganisms, influences bioavailability to organisms as well as the potential for adverse effects.

Microplastics have been detected in more than 1300 aquatic and terrestrial species, including fish, mammals, birds, and insects (Fig. 3) (23, 58, 63), and effects are evident at all levels of biological organization, from the subcellular level to the stability of food webs (64–66). Ingestion can lead to physical harm, such as food dilution, gastrointestinal blockage, or internal abrasion (65, 66), and chemical harm as a result of the leaching of toxic additives or adsorbed pollutants, including endocrine disrupting chemicals, from the microplastics (67, 68). The absorption of the smallest particles by the body can lead to toxicity triggered upon translocation (69), for which the surface area of the microplastic is considered the toxicologically relevant dose metric (70). Effects vary widely according to the organism and the type and quantity of microplastics ingested, but end points with direct ecological relevance, including reduced growth, survival, and reproduction, have all been demonstrated in laboratory experiments. Whether the particles and chemical substances show effects under natural exposure conditions strongly depends on the circumstances (71–73), but effects at environmentally relevant concentrations have been demonstrated (74).

Table 1. Estimated quantities of microplastics entering the marine environment annually. The major sources of microplastics and their relative contribution in kilotonnes as reported in various publications. This also includes macroplastics, which will eventually fragment into microplastics; their contribution is illustrated as typical annual leakage to the ocean. Note that each study used different methods; where possible, the range is shown with a central value in parentheses, and averages and standard deviations are used in Fig. 2B. Blank cells indicate that the study did not evaluate this source.

Source	Boucher and Friot (13)	UNEP (34)	PEW and Systemiq (14)	Paruta *et al.* (15)	Jambeck *et al.* (43)	OECD (185)	Ryberg *et al.* (186)	Earth Action (45)	Average quantity	Standard deviation
Personal care products	30	10	200				10.963	36	57	80.54
Pellets	5	30	200			432	9	848	254	334.58
Paint	156			1900				1846	1301	991.68
Synthetic textiles	522	260	40			135	219	88	211	172.82
Tires	424	1410	1000			648	1410	946	973	397.60
Macroplastics (becoming micro)		5270	11,000		4800–12,700 (8000)	6000			7568	2562.85

Understanding the environmental impacts of microplastics has become a pressing concern, with a growing need to quantify effects within risk assessments (*38*, *75*). The scientific community has faced challenges in developing testing and assessment strategies for microplastics, which are complex and heterogeneous, because of variations in chemical composition, age, and environmental weathering. Initial laboratory studies that tested monodisperse plastics at relatively high concentrations provided valuable insights and a mechanistic understanding of microplastics. Consideration of risk assessments highlighted discrepancies between laboratory experiments and real-world conditions, such as the overrepresentation of certain polymers and species, and emphasized the importance of experiments at environmentally realistic concentrations (*76*). Researchers are increasingly stressing the need for detailed particle characterization, relevant controls, and the consideration of environmental relevance in terms of particle size and chemical composition (*77*, *78*). The need for characterization has resulted in the development of definitions for plastic particles [Fig. 1; (*10*, *55*)] and a recognition of the importance of environmental transformation of microplastics. Despite such advancements, challenges remain in data comparability and our understanding of the mechanisms behind microplastic effects, with a noted imbalance in the types of plastics and species studied; for example, earthworms are most commonly used in terrestrial tests, and 62% of all toxicity assessments have used polystyrene or polyethylene particles (*66*).

In 2020, an innovative quantitative tool was introduced to assess the validity of studies and its use revealed substantial gaps in relevance for regulatory risk assessments (*66*). Furthermore, guidelines were published to improve the comparability and reproducibility of microplastic research (*79*, *80*). These developments mark steps toward addressing the complexities of microplastic pollution, emphasizing the need for comprehensive and realistic testing methods to better understand and mitigate the environmental impacts of microplastics. Fully aligned and quality assurance– or quality control–screened ecological risk assessment frameworks have now been published for freshwater, marine waters, sediments, and soils, and some of these have been adopted in a regulatory context (*60*, *81*, *82*). Together with quality assurance and quality control evaluation tools to minimize inherent bias, which may exist within studies, these frameworks are robust and capable of quantifying risk measures. Studies that apply these frameworks confirm that ecological risks have been detected at microplastic hotspot locations. These will become more widespread as particle numbers increase, and modeling predictions (*62*) indicate the potential for wide-scale ecological risk within the next 100 years if contamination of the natural environment continues at the present rate.

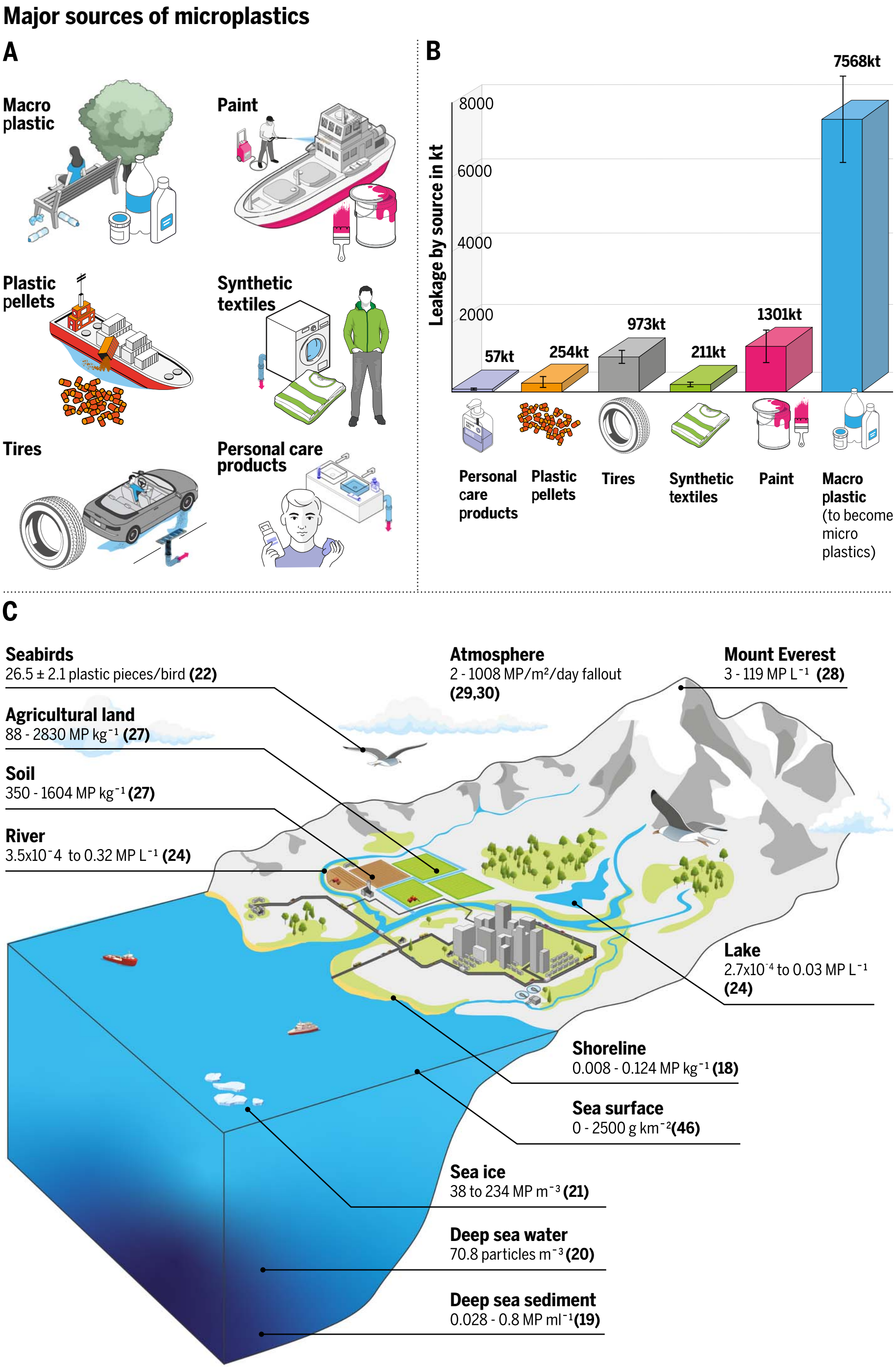


Fig. 2. Sources and pathways that lead to environmental accumulation of microplastics. (**A**) Human activities that lead to six key sources of microplastics, (**B**) the relative contribution of each to the marine environment (for source data, see Table 1), and (**C**) quantities reported in various environmental compartments. Note that intercomparisons between environmental compartments should be made with caution because of variations in methods of sampling and enumeration. kt, kilotonnes; MP, microplastics. [Figure credit: J. Beadon]

Several key knowledge gaps remain; for example, it is unclear what the concentrations of nanoplastics are in the environment or, indeed, how we should measure and test them, and thus also what their environmental behavior is and what the effects on individual organisms and communities are (*38*, *82*). The rate of formation of micro- and nanoplastics in nature is insufficiently understood but is of considerable importance for scenario analyses in relation to

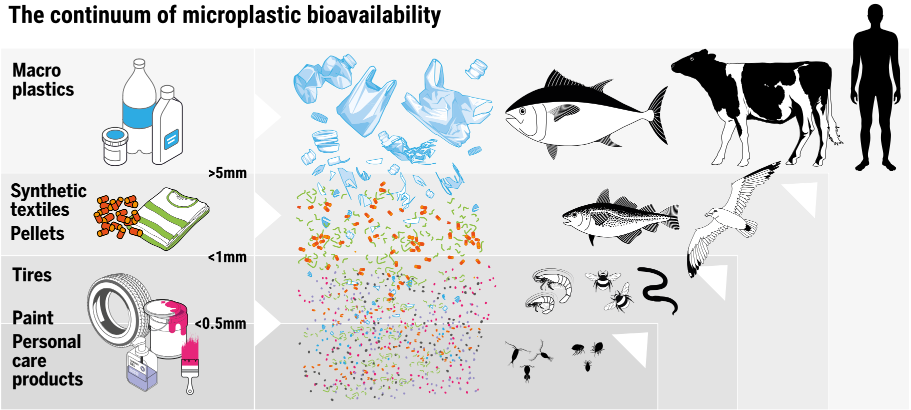


Fig. 3. Bioavailability of plastics and microplastics, according to size and key sources. As plastic items fragment into ever smaller pieces, they become available to a wider range of organisms (descending horizontal rows) and the potential for transfer along food chains also increases (diagonal arrows). [Figure credit: J. Beadon]

estimates of future plastic production, waste management, and environmental accumulation. Finally, we emphasize that if knowledge and data gaps still exist regarding the assessment of the risks of microplastics, policy action does not have to wait but should, on the basis of the evidence that is available, be justified by adopting the precautionary principle (*83*, *84*).

Understanding the risks of microplastics to human health

Microplastics are pervasive and have been identified in the water we drink, the air we breathe, and the food we eat, including seafood, table salt, honey, sugar, and beverages such as beer and tea (*85*–*89*). In some instances, contamination of our food occurs in the natural environment; however, processing, packaging, and handling can further contribute to microplastic contamination (*90*, *91*). Reported concentrations are highly variable, which directly influences exposure levels among individuals globally (*86*). Methods of quantification also vary, which introduces uncertainty within exposure assessments. In addition, there is limited data on microplastics in terrestrial animal products, cereals, grains, fruits, vegetables, some beverages, spices, condiments, baby foods, and edible oils and fats (*91*). Although it is now certain that, as with numerous other organisms and other types of contaminants, humans are exposed to microplastics, quantities have, in some instances, been grossly overestimated, such as the weight of a credit card per week (*92*).

Over the past few years, microplastics have been reported in various human tissues, organs, and bodily fluids (*93*–*96*). They have been detected in human blood, placenta, liver, and kidney (Fig. 4), which indicates their ability to traverse the body (*97*–*106*). They are also eliminated from the body via feces, urine, and exhalation (*96*, *107*, *108*). Elimination efficiency varies according to characteristics of the particle and the condition and behavior of individuals; for example, higher concentrations of microplastics are reported in the lungs of smokers than in those of nonsmokers (*109*). Animal studies, particularly those on rodents, have offered preliminary insights into how microplastics are transported within the body, as well as their accumulation and elimination processes. Quantitative in vitro to in vivo extrapolation (QIVIVE) and pharmacokinetics [physiologically based kinetic (PBK)] modeling can improve our understanding of how microplastics are absorbed, distributed, metabolized, and excreted; these will be crucial in order to translate laboratory findings into predictions about the human health risks of microplastics (*110*, *111*). Such approaches may also be influenced by recent reports on the potential for an association between microplastics and various diseases, including cardiovascular disease (*112*).

Toxicological assessment of microplastics involves quantifying exposure and evaluating potential health impacts. Toxicologically relevant dose metrics for microplastics aim to quantify exposure and evaluate health impacts across ecosystems and organisms, including humans (*111*, *113*). These metrics consider microplastics' exposure concentration, size, shape, polymer identity, and composition of plastic-associated chemicals (*91*). Important toxicologically relevant dose metrics include particle volume and surface area or specific surface area (*114*, *115*), which all affect interactions with biological systems, and the size and shape of the particles, which have been shown to affect bioavailability and bioaccessibility in the human body (*93*).

Epidemiological effect assessment requires the evaluation of biological end points such as inflammation, oxidative stress, immunoresponses, and genotoxicity, which are influenced by the physiochemical characteristics of the microplastic and are often dose-dependent. Effects of nano- or microplastics on cells or tissues have already been demonstrated in vitro (*85*, *93*, *116*). However, these laboratory experiments often used relatively high concentrations of particles that may not sufficiently resemble the quantities and types of particles that humans are presently exposed to (*117*). Hence, it is difficult to translate experimental results to in vivo effects, especially over long-term chronic exposures, which are likely to be most applicable to human exposure scenarios (*91*, *118*). Another challenge lies in the complexity and variability of the biocorona, a layer of molecules, such as proteins, lipids, or polysaccharides, that adhere to the surface of microplastics when they come into contact with biological fluids (*119*). This could include toxins or antigens and may substantially alter the physical and chemical properties of microplastic particles, including their effective size, charge, and hydrophobicity, and, consequently, their biological interactions (*85*).

Our ability to conduct risk assessments for human exposure is presently limited because exposure and effect assessments are fragmentary and incomplete. Tools, frameworks, and strategies to enable consistent risk assessment are available (*86*, *111*), and work is underway to obtain the necessary exposure data and effect information. In the next 5 to 10 years, we therefore anticipate greater clarity on the extent to which various types of microplastics could cause effects on human health. Meanwhile, there is clear evidence of growing public concern about the potential for such effects (see section Human decisions and actions as causes and solutions of microplastic pollution) and the wider human health and social justice implications (*120*). In addition, given the persistence of microplastic and the near impossibility of their removal once dispersed in the environment, an increasing emphasis should be placed on taking a precautionary approach (*84*).

Methodological advances

In parallel with, and complementary to, the growing understanding of the types, concentrations, and effects of microplastics, there have been advances in their detection. Some of the first approaches to isolate microplastics from sediments were based on density separation (*8*, *121*), using solutions of sodium or zinc chloride. Acid and alkali digestions have been used to separate microplastics from organic-rich matrices, including biota and sewage sludge (*122*), and more recent developments include less-aggressive enzymatic approaches (*123*, *124*) and the use of Fenton's reagent (*125*). Concurrently, awareness of the potential for sample contamination or bias during collection and processing has led to quality control and assurance measures (*126*, *127*), which are vital for robust risk assessments (see sections Ecological impacts and risks and Understanding the risks of microplastics to human health). For example, early seawater sampling used nets with 333-µm mesh (*4*, *5*), but more recently, the use of smaller apertures and filtration has revealed substantially higher concentrations of microplastics than first estimated (*128*), including the presence of nanoplastics (*129*). Analyzing smaller particle sizes has also enabled more accurate quantifications according to sources; for example, recent work has shown that a 5-kg load of polyester clothing can release up to 6 million microfibers (≥5 µm) (*130*), about 10 times more than initial estimates obtained by using a 25-µm filter (*131*).

Polymer identification has long used Fourier transform infrared (FTIR) spectroscopy (*5*) and, more recently, Raman spectroscopy (*132*), and open-source spectral libraries and software have been made available to facilitate data processing (*133*, *134*). However, FTIR is not without its limitations because spectral acuity is reduced for degraded plastics, and small (<20 µm) and black particles are hard to resolve (*135*). Recently, pyrolysis–gas chromatography–mass spectroscopy (py-GC-MS) has considerably advanced our ability to indicate the presence of tire-wear particles (*136*), which were not possible to identify with spectrometry because of their small size and dark coloration. Py-GC-MS quantifies by mass and can include particles that would be too small for spectroscopic approaches, for example, particles in the human body (Fig. 4), including in the blood (*99*), and nanoplastics (*137*). However, it does not provide information about numerical abundance or particle size or shape, all of which can influence toxicological effects. Chemical markers associated with a range of polymers, including bio-based or biodegradable plastics, have been developed for use with py-GC-MS (*138*); as with any "marker," the outcomes are an indicator of the amount present and, unlike direct counts, will be influenced by other sources of the marker concerned. In addition to improved detection from environmental samples, laboratory experiments that use particles with fluorescent (*123*), metal-doped (*139*), and radio labels (*140*, *141*) have advanced our understanding of uptake and retention at environmentally relevant doses in plants and animals.

This diverse array of methods has advanced the field immensely in recent years, and there are increasing calls to standardize approaches and reporting of units to facilitate intercomparability [e.g., (*70*, *142*)]. Although this is clearly important, each method has its limitations, and the approach should be guided by the scientific question. Innovative methods such as py-GC-MS allow an ever-more-detailed mechanistic understanding of the fate, behavior, and impacts of plastic particles and associated chemicals but are expensive and time consuming. By contrast, environmental monitoring requires consistent rapid high-throughput approaches. At present, there is no universal approach for sampling and characterizing microplastics, and care must be taken to align the approach with the question concerned and to be aware of and communicate any limitations. There is an urgent need for a harmonization of monitoring approaches, and these should be guided by our understanding of harm in relation to specific types and sources of microplastic (*143*) (see sections Ecological impacts and risks and Understanding the risks of microplastics to human health). Critically, there will be a need to develop new monitoring approaches that directly assess the efficacy of any interventions that are adopted.

Human decisions and actions as causes and solutions of microplastic pollution

Scientific publications on sources and ecological and human health effects of microplastics outline available evidence on microplastic pollution but do not typically analyze the communication and reception of such evidence or the broader social drivers of plastics use. Microplastic pollution is the consequence of human decisions and actions (*144*), and understanding these social dynamics is key to designing effective solutions. Scientific evidence is filtered through social interpretations, and decision-makers in policy and industry are sensitive to public perceptions and their effects on voting, reputation, and image. The humanities and social and behavioral sciences can make important contributions here (*144*).

Why did plastic materials and products become so successful in the first place? Plastics were developed by chemists in the 19th and 20th centuries, and writers (*145*) in the 1930s speculated that these new materials might even reduce global conflict (*145*). Wide-scale commercial success followed in the 1950s when mass production put numerous lightweight durable consumer products on the market. Ensuing cultural commentary was largely positive, as illustrated by films such

Microplastics in the human body

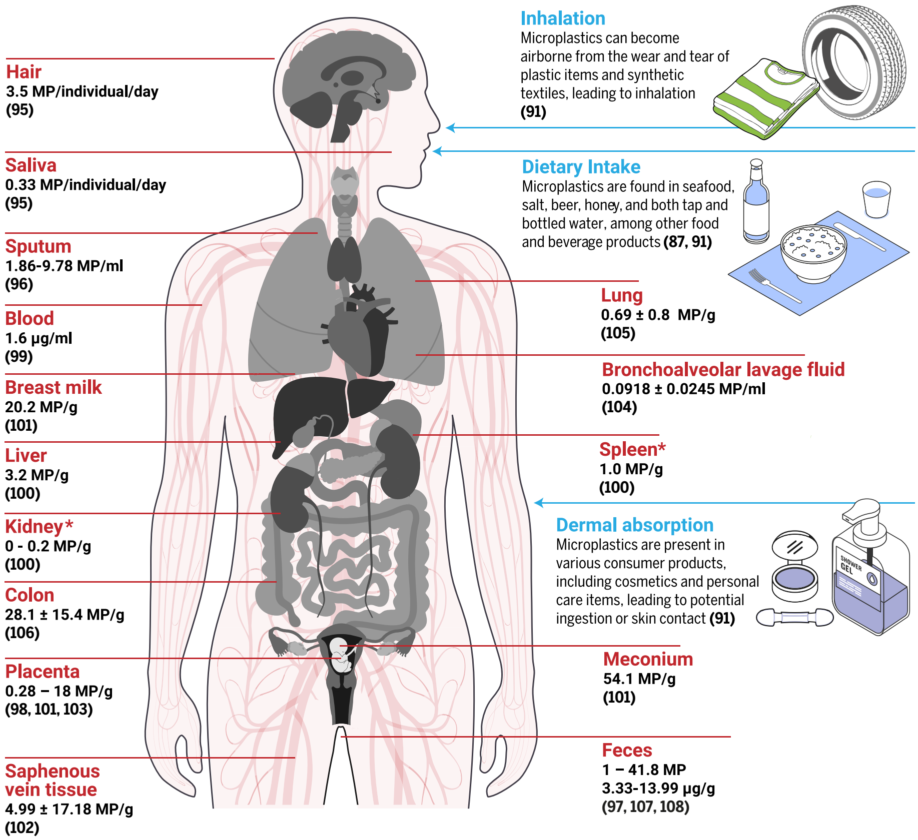
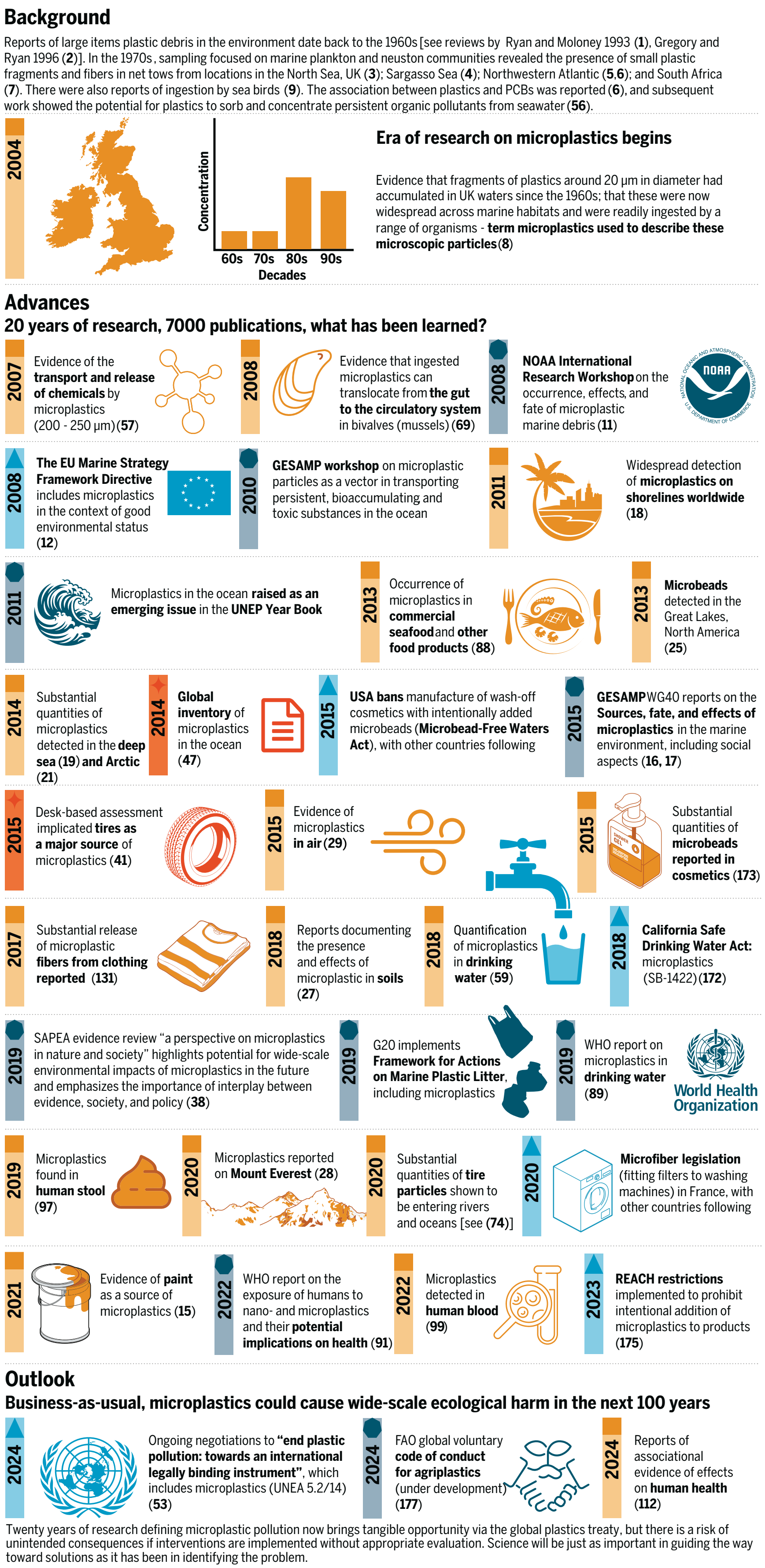


Fig. 4. Locations in the human body where microplastics have been reported. Exposure pathways (turquoise labels) and reported quantities (red labels) are shown. Quantities of microplastics (MP) are as reported in each study and have not been further quality assurance and quality control–screened for this review. Intercomparisons should be made with caution because of variation in methods and units of reporting between studies. Because some methods do not characterize individual particles, it is likely that quantities reported by mass relate to both micro- and/or nanoparticles (see section Methodological advances for discussion). *Quantities reported as being around the limit of detection. [Figure credit: J. Beadon]

as *The Graduate* (1967) (*146*), and today, plastics are ubiquitous in daily life, from homes and clothes to medical care and technology. The immense externalized indirect costs to the environment and society from present practices of plastic production, use, and disposal have been presented (*120*) (see section Sources, transport, distribution, and environmental concentrations of microplastics through section Methodological advances), yet the success of plastics is driven by the convergence of producer and consumer needs and benefits, through being convenient and affordable to make and use.

At the same time, societal concern is increasing (*147*). Although public risk perceptions are responsive to "objective" risk information (see sections Ecological impacts and risks and Understanding the risks of microplastics to human health), they also integrate more subjective psychological and social factors, such as fairness, values, emotions, and social norms (*144*, *148*). Public concern about plastic in the ocean recently ranked higher than concern about climate change in both Australia and the United States (*149*, *150*). In addition, Europeans and Australians regarded plastic pollution as the biggest marine-related threat to human health, followed by chemical or oil pollution (*151*), and 88% of citizens across 28 European countries recently expressed worry about the environmental impact of microplastics ["tend to agree" or "totally agree" (*152*)]. Although concern about microplastics affecting human health has been less pronounced than concern for the environment (*153*, *154*), the situation is rapidly evolving. Since 2023, German consumers have rated microplastics in food as their top health concern (*155*). Human health and food risks are particularly sensitive topics in society [e.g., (*156*)], and participants in some studies now express concern about microplastics being linked to specific human health conditions such as cancer (*154*, *157*). Such concerns may trigger public demand for action, and strong public support for policy measures against plastic pollution has recently been shown [e.g., in a Swedish sample (*158*)]. Overall, public opinion data indicate concern and a desire for action.

Which actions should be prioritized (*159*)? As with all complex problems, no single action will suffice and concerted efforts and consensus between different actor groups are required.



Background

Reports of large items plastic debris in the environment date back to the 1960s [see reviews by Ryan and Moloney 1993 (**1**), Gregory and Ryan 1996 (**2**)]. In the 1970s, sampling focused on marine plankton and neuston communities revealed the presence of small plastic fragments and fibers in net tows from locations in the North Sea, UK (**3**); Sargasso Sea (**4**); Northwestern Atlantic (**5**,**6**); and South Africa (**7**). There were also reports of ingestion by sea birds (**9**). The association between plastics and PCBs was reported (**6**), and subsequent work showed the potential for plastics to sorb and concentrate persistent organic pollutants from seawater (**56**).

2004 **Era of research on microplastics begins**

Evidence that fragments of plastics around 20 μm in diameter had accumulated in UK waters since the 1960s; that these were now widespread across marine habitats and were readily ingested by a range of organisms - **term microplastics used to describe these microscopic particles** (**8**)

Advances

20 years of research, 7000 publications, what has been learned?

2007 Evidence of the **transport and release of chemicals** by microplastics (200 - 250 μm) (**57**)

2008 Evidence that ingested microplastics can translocate from **the gut to the circulatory system** in bivalves (mussels) (**69**)

2008 **NOAA International Research Workshop** on the occurrence, effects, and fate of microplastic marine debris (**11**)

2008 **The EU Marine Strategy Framework Directive** includes microplastics in the context of good environmental status (**12**)

2010 **GESAMP workshop** on microplastic particles as a vector in transporting persistent, bioaccumulating and toxic substances in the ocean

2011 Widespread detection of **microplastics on shorelines worldwide** (**18**)

2011 Microplastics in the ocean **raised as an emerging issue** in the **UNEP Year Book**

2013 Occurrence of microplastics in **commercial seafood** and **other food products** (**88**)

2013 **Microbeads** detected in the Great Lakes, North America (**25**)

2014 Substantial quantities of microplastics detected in the **deep sea** (**19**) **and Arctic** (**21**)

2014 **Global inventory** of microplastics in the ocean (**47**)

2015 **USA bans** manufacture of wash-off cosmetics with intentionally added microbeads (**Microbead-Free Waters Act**), with other countries following

2015 **GESAMP** WG40 reports on the **Sources, fate, and effects of microplastics** in the marine environment, including social aspects (**16, 17**)

2015 Desk-based assessment implicated **tires as a major source** of microplastics (**41**)

2015 Evidence of microplastics **in air** (**29**)

2015 Substantial quantities of **microbeads reported in cosmetics** (**173**)

2017 Substantial release of microplastic **fibers from clothing reported** (**131**)

2018 Reports documenting the presence and effects of microplastic in **soils** (**27**)

2018 Quantification of microplastics in **drinking water** (**59**)

2018 **California Safe Drinking Water Act:** microplastics (SB-1422) (**172**)

2019 SAPEA evidence review "a perspective on microplastics in nature and society" highlights potential for wide-scale environmental impacts of microplastics in the future and emphasizes the importance of interplay between evidence, society, and policy (**38**)

2019 G20 implements **Framework for Actions on Marine Plastic Litter**, including microplastics

2019 WHO report on microplastics in **drinking water** (**89**)

2019 Microplastics found in **human stool** (**97**)

2020 Microplastics reported on **Mount Everest** (**28**)

2020 Substantial quantities of **tire particles** shown to be entering rivers and oceans [see (**74**)]

2020 **Microfiber legislation** (fitting filters to washing machines) in France, with other countries following

2021 Evidence of **paint** as a source of microplastics (**15**)

2022 WHO report on the exposure of humans to nano- and microplastics and their **potential implications on health** (**91**)

2022 Microplastics detected in **human blood** (**99**)

2023 **REACH restrictions** implemented to prohibit intentional addition of microplastics to products (**175**)

Outlook

Business-as-usual, microplastics could cause wide-scale ecological harm in the next 100 years

2024 Ongoing negotiations to **"end plastic pollution: towards an international legally binding instrument"**, which includes microplastics (UNEA 5.2/14) (**53**)

2024 FAO global voluntary **code of conduct for agriplastics** (under development) (**177**)

2024 Reports of associational evidence of effects on **human health** (**112**)

Twenty years of research defining microplastic pollution now brings tangible opportunity via the global plastics treaty, but there is a risk of unintended consequences if interventions are implemented without appropriate evaluation. Science will be just as important in guiding the way toward solutions as it has been in identifying the problem.

Fig. 5. The era of microplastic research. Timeline illustrating key events in the history of microplastic research along with examples of key empirical research (light orange), reviews (dark orange), policy-focused expert reports (light blue), and legislation (dark blue) that directly or indirectly followed the 2004 paper "Lost at sea: Where is all the plastic?" (*8*). [Figure credit: J. Beadon]

Many actions to date have focused on downstream, end-of-pipe solutions (*160*), but there is growing recognition that upstream and whole-system life-cycle approaches, including reducing production and circular economy, are needed, which account for externalities from material extraction to remediation (*161*, *162*). Upstream measures require substantial changes in societal practices and rely on social acceptance and economic feasibility of new materials, products, and systems by industry, the workforce, and consumers. Individuals and communities are now instigating legal action to achieve change through litigation, using both private and public law (*163*, *164*). Finally, research has begun to systematically assess the effectiveness of behavioral interventions (*144*, *147*, *165*–*168*).

How do we navigate decision-making and create a consensus on actions when there is concern in the public and media (*169*, *170*) but some gaps and uncertainty in scientific evidence on microplastics remain [(*38*, *91*); see sections Ecological impacts and risks and Understanding the risks of microplastics to human health]? The precautionary principle (*83*, *84*) aims at preventing harm where early warnings about hazards exist, especially given evidence that long-term risks may not be anticipated at the point of innovation of technologies, materials, or substances (*84*). Part of this principle is also that the public is "involved in decisions about serious hazards and their avoidance, and at all stages of the risk analysis process" (*84*). For such engagement to be effective and equitable, we need to understand factors that drive risk perception and support for measures at individual, community, and societal levels of analysis (*144*, *171*). We posit that rigorous research is key not just to establishing evidence of harm and risk of microplastics but also to obtaining solid evidence on associated sociopolitical dynamics, including risk communication and evaluation of interventions in terms of social and environmental outcomes (*169*, *170*). Needless to say, methodological research standards are applied here just like in the natural sciences, including data synthesis, sampling and analytic protocols, correlational and causal analysis, and best-practice survey design to minimize bias [see (*144*)].

Regulatory options to address microplastics

A range of policy initiatives have been influential in catalyzing the need for regulation. For example, the EU Marine Strategy Framework Directive (*12*) included microplastics as a component to be measured toward establishing good status of the marine environment. In addition, the California Safe Drinking Water Act (SB-1422) mandated testing and disclosure of microplastics in drinking water (*172*), and recently at a global level, the draft global plastics treaty (*53*) recognized microplastics as a key aspect of plastic pollution, along with plastic materials and products and plastic-related chemicals (see preamble). The challenge, however, will lie in the detail of how to address the multiple sources and pathways for microplastics (see section Sources, transport, distribution, and environmental concentrations of microplastics).

Regulating and monitoring primary microplastics that are manufactured at sizes ≤5 mm and that are intentionally added to products (Fig. 1) can be relatively straightforward; for example, microbeads added to cosmetics (*31*, *173*) have been banned in at least 14 countries, as well as in the European Economic Area, which has 30 member countries (*174*). And in 2023, the EU chemical legislation REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) expanded this ban to all products that contain intentionally added microplastics (*175*). The draft global plastics treaty (*53*) aims to address primary microplastics as "problematic and avoidable" (Part II.3), potentially establishing a global ban on production, use in manufacturing, sale, distribution, import, or export of products to which microplastics are intentionally added. An additional major upstream source of primary microplastic pollution is spillage, during transportation, of preproduction pellets, powders, and flakes that are used to manufacture plastic products. Here, regulations on transportation by the International Maritime Organization under the International Maritime Dangerous Goods (IMDG) Code and required disclosure by insurance companies could be effective but will need to include preproduction materials of all sizes, not just those <5 mm. In addition, some niche products such as plastic confetti or glitter may require specific policy measures because they are used directly rather than intentionally added to another final product (Fig. 1).

Secondary microplastics are more complex to regulate. Apart from legislation on oxo-degradable plastics, which have been banned in the United States and EU in recognition of their breakdown into microplastics (*176*), most regulations (Fig. 1) have targeted mitigation after generation, for example, washing machine filters that capture microfibers, which have been legislated in France (2020), and infrastructure at sewage treatment plants to capture microplastics. However, these interventions are unlikely to provide net environmental benefits if filters are not cleaned correctly or if sludge from sewage treatment that contains captured microplastics is subsequently applied to soils as nutrient enrichment (*51*).

There is growing evidence that upstream approaches will be most effective. Here, redesign could be incentivized through market-based instruments, such as mandatory design and performance criteria and ecomodulated taxes based on release rates. For example, better design of yarns and textiles could substantially (by around 80%) reduce rates of microfiber release during laundering as well as while garments are being worn (*130*, *131*). Products that are directly used in, and are difficult to remove from, the environment are also of specific concern. For example, mulch films protect agricultural crops, but ultraviolet radiation, among other factors, accelerates their breakdown into microplastics. In addition, fishing gear, such as dolly ropes, generate microplastics while in use, and these are released directly into the environment. Agri-plastics such as these are the focus of the global Food and Agriculture Organization of the United Nations (FAO) voluntary code of conduct (*177*), which is under development. Consideration must also be given to an ambiguity in the draft text for the global plastics treaty, which uses the phrase "unintentional releases"; this creates a potential loophole because the functionality of products such as tires and dolly ropes necessitates their wear, making microplastic release intentional rather than unintentional. Generation of microplastics in waste management, for example, from recycling plants, has also recently been highlighted as a concern (*36*). Under the draft global plastics treaty, releases of secondary microplastics that originate from degradation while products are in use or from waste management streams (Fig. 1) could be addressed under the proposed measures for emissions and releases across the plastics life cycle (Part II of the draft global plastics treaty; also see section Outlook and evidence needs). Some countries have suggested that a reduction of secondary microplastic releases could be incorporated under measures for product design, composition, and performance (Part II.5 of the draft global plastics treaty), with the aim of addressing the safety, durability, reusability, refillability, repairability, and refurbishability of products generally. Ensuring product safety will require the strong regulation of chemicals and polymers of concern that are used in plastics, as proposed in Part II.2 of the draft global plastics treaty, and assessment should start by considering the essentiality of problematic products, associated chemicals, and microplastics (*178*).

Secondary microplastics that result from the breakdown of macroplastics in the environment (Fig. 1) are best addressed through measures that aim to minimize the release of macroplastics to the environment in the first place. This includes reducing production, improving product design, and promoting nonplastic substitutes, as well as improved waste management. In some very specific locations, cleanup of macroplastics from the environment may be beneficial as a long-term strategy to help minimize their breakdown into microplastics. However, there is also evidence that mechanical cleanup devices can harm marine life (*179*, *180*), which emphasizes the critical importance of independently evaluating any potential intervention across a range of societal contexts before it is adopted (*181*).

On the basis of existing legislation and the diversity of sources and pathways by which microplastics enter the environment, a range of measures will be needed (Fig. 1), taking sectoral and source-based approaches that consider regional differences in essentiality and waste management infrastructure. Key requirements for success under the global plastics treaty are baselines and targets to reduce production and consumption as well as safety, sustainability, and essentiality criteria relating to the life cycle of plastic products and the chemicals they contain (*182*) in addition to measures to ensure a just transition, for example, in relation to the livelihoods of waste pickers in the informal sector (*183*). In our view, the associated evidence needs will require a dedicated science-policy interface to the global plastics treaty that is not compromised by conflicts of interest (*184*).

Outlook and evidence needs

After more than 20 years of research focused specifically on microplastics, there is extensive evidence of the key sources (Figs. 1 and 2B) and wide-scale environmental accumulation (Fig. 2C). Toxicological effects have been confirmed across all levels of biological organization (Fig. 3), and there is evidence of potential effects on human health (Fig. 4) as well as increasing societal interest and initial policy responses (Fig. 5).

Environmental concentrations and bioavailability will increase into the future. If knowledge and data gaps still exist regarding the assessment of the risks of microplastics, then policy action does not have to wait—it can be justified on the basis of the precautionary principle, and so measures can, and arguably should, be taken now to reduce emissions. Bans on unnecessary and avoidable plastic products and applications and better product design, together with associated changes in behavior along supply chains, offer considerable promise, but there is a high risk of unintended consequences if interventions are implemented without appropriate evaluation and consideration of the relevant sociotechnical and geographic contexts. In our view, science will be just as important in guiding the way toward solutions as it has been in identifying the problems. The global plastics treaty now brings tangible opportunity for international actions. The evidence summarized in this review emphasizes that although measures on macroplastic are of critical importance, these alone will be insufficient to address the multitude of sources outlined above (see section Sources, transport, distribution, and environmental concentrations of microplastics), and dedicated provisions on microplastic pollution will be essential.

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