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

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Twenty years after the first publication using the term microplastics, 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 widescale harm has been predicted. Public concern is increasing and diverse measures to address microplastics 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 (~20µm 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 ≤5mm in size, composed of polymers together with functional additives as well as other intentionally and unintentionally added chemicals (*10*). While not following the SI convention of units (Fig. 1E), this size definition resulted from an early policy meeting hosted by NOAA in Tacoma, USA (*11*), which proposed this upper size bound (Fig. 1E), because of evidence that particles up to 5mm could readily be ingested by organisms and growing concerns they might present different risks to larger items that were already known to cause harm. The EU subsequently adopted this upper bound of 5mm in its Marine Strategy Framework Directive (MSFD) (*12*). In most studies the lower size bound is typically constrained by methodological limitations to the minimum size of particles it is possible to isolate and identify from complex environmental mixtures (see section Methodological advances). Below >1µm we move from micro to nano and while nano-sized plastic particles have almost certainly accumulated, they are currently too small to individually identify from environmental samples.

Subcategories of microplastic linked to source have since been described, including the terms '*primary*' and '*secondary*' microplastics, but this terminology has not been used consistently (*10*). This is especially so for particles and fibers generated by wear, with multiple publications considering these to be primary microplastics [e.g., (*13*–*15*)], the remainder 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. 1) incorporating recently described sources and resulting in three categories of primary microplastics, which are manufactured ≤5mm, and three categories of secondary microplastic, which all originate from items that are >5mm at manufacture, either as a consequence of wear during use, or from fragmentation in waste management, or the environment. Other terms aligned with primary and secondary that have been used in policy contexts, including draft text for the UN Plastic Pollution Treaty, include "intentionally added microplastics" and microplastics that are "unintentionally" released or generated by degradation (Fig. 1).

Sources, transport, distribution, and environmental concentrations of microplastics

Over the past two decades hundreds of papers have specifically focused on the environmental accumulation of microplastic, including on shorelines (*18*), in the deep sea (*19*), the water column (*20*) and sea ice (*21*) as well as 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 Mt Everest (*28*) and in the atmosphere (*29*, *30*) and 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 pre-production pellets (based on the <5mm definition) (*32*, *33*) and fragmentation of larger items (*8*), while paints, tire abrasion (Fig. 1C), construction and pre-production 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 microplastics 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 is, at end of life, the cause of extensive accumulation of plastics in waste streams and the environment. Degradation and biodegradation are both systems properties influenced by the plastic material and its receiving environment; with exposure to ultraviolet light, heat, humidity and aerobic conditions generally increasing chemical deterioration, coupled with 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, nor is the extent to which microplastics potentially fragment into nanoplastics, nor are the timescales required for plastics to be mineralized. Greater understanding of these transformation rates would be invaluable to risk assessment (section Ecological impacts and risk and section Understanding the risks of microplastics to human health) however the rate of mineralization would appear to be miniscule compared to 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 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 microplastic. A recent expert group review concluded that while biodegradable plastics could bring benefit 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. 2, A and B), including studies in Nordic countries (*41*, *42*) and the IUCN's 2020 global assessment which estimates a combined total of between 0.8 - 3 million tons per annum (*13*).While rates of fragmentation have not yet been derived, we also highlight the importance of macroplastics as a source of microplastic to the marine environment by illustrating the annual leakage of macroplastic to the ocean as a proxy (Fig. 2B; 7.6 MT/year) (*43*, *44*). In addition, a recent report suggests leakage into terrestrial environments could be 3 – 10 times greater than that to the marine environment giving a total of around 10 - 40 Mt 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; highlighted in an article on “the missing plastic” (*46*, *47*). Recent studies have resolved this by quantifying microplastics in locations that had previously been overlooked such as those suspended in the water column; together with recent investigations into the amount of plastic present as smaller size fractions (≥ 10μm) which are harder to detect (*48*).

Points of entry to 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 resulting 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 highlighting the importance of actions at a global level (*53*) (section Regulatory options to address microplastics). Rivers are recognized as major pathways connecting sources inland with the marine environment, and redistribution of finer airborne microplastic by wind is likely to be a 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*). While 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 unique differences compared natural particulates and makes extrapolation challenging (*55*).

As new sources, pathways, and hotspots of environmental contamination are identified it is important to emphasize that while 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. Considering the multiple sources, pathways, and broad environmental distribution, addressing microplastics at source is imperative. To underscore the urgency, forecasting models indicate that, under business-as-usual scenarios, microplastic leakage to the environment could rise 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 items of plastic that are already present. The overarching message is clear, environmental concentrations and exposure of biota and humans are set to increase.

Ecological impacts and risks

The bioavailability of microplastic to invertebrate filter feeders, deposit feeders and detritivores as well as birds and fish has been recognized for some time and is important because of the potential for plastics to adsorb, transport and release chemicals as well as the potential for particle toxicity (*56*, *57*). Evidence of microplastic accumulation across multiple ecosystems (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, influence 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, due to 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 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 endpoints 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 concentration have been demonstrated (*74*).

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 testing monodisperse plastics at relatively high concentrations provided valuable insights and a mechanistic understanding of microplastics. While consideration of risk assessment 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 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, a novel quantitative tool was introduced to assess the validity of studies and revealed significant 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/ Quality Control (QA/QC) 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 QA/QC evaluation tools to minimize inherent bias which may exist within studies, these frameworks are robust and capable of quantifying risk measures. Studies applying 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 widescale ecological risk within the next 100 years if contamination of the natural environment continues at the current rate.

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 behavior and effects are on individual organisms and communities (*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 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 like 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, directly influencing exposure levels among individuals globally (*86*). Methods of quantification also vary, introducing 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*). While it is now certain, and perhaps unsurprising, that, as with numerous other organisms and other types of contaminant, 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 last few years microplastics have been reported in various human tissues, organs, and bodily fluids (*93*–*96*). They have been detected in human blood, the placenta, liver and kidney (Fig. 4) indicating 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 microplastic are reported in the lungs of smokers compared to non-smokers (*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 (PBK) modeling can help 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 health (*112*).

Toxicological assessment of microplastics involves quantifying exposure and evaluating potential health impacts. Toxicologically relevant dose metrics (TRMs) 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 TRMs are particle volume, surface area or specific surface area (*114*, *115*), which all affect the interaction with biological systems, while the size and shape of the particles have been shown to affect bioavailability and bioaccessibility in the human body (*93*).

Epidemiological effect assessment requires evaluation of biological end points such as inflammation, oxidative stress, immuno-responses and genotoxicity, which are influenced by the physio-chemical characteristics of the microplastic and often are 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 currently 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, hydrophobicity, and, consequently, their biological interactions (*85*).

Our ability to conduct risk assessments for human exposure is currently 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 five to ten 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 (section Human decisions and actions as causes and solutions of microplastics pollution) and the wider human health and social justice implications (*120*) and, 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*), in addition to the more recent development of 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 (section Ecological impacts and risks and section Understanding the risks of microplastics to human health). For example, early seawater sampling used nets with 333µm mesh (*4*, *5*), but more recently smaller apertures, and filtration have revealed substantially more microplastics than first estimated (*128*), including the presence of nanoplastics (*129*). Analyzing smaller particle sizes also enabled more accurate quantification according to sources; for example, recent work has shown a 5kg load of polyester clothing can release up to 6 million microfibers (≥5 µm) (*130*), ca. 10-times more than initial estimates using a 25 µm filter (*131*).

Polymer identification has long utilized 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 as spectral acuity reduces 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 via spectrometry because of their small size and dark coloration. Py-GC-MS quantifies by mass and has the ability to 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 of numerical abundance, particle size or shape, all of which can influence toxicological effects. Chemical markers associated with a range of polymers including bio-based/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, using 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 units to facilitate inter comparability [e.g., (*70*, *142*)]. While this is clearly important, each method has its limitations and the approach should be guided by the scientific question. Novel methods such as py-GC-MS allow 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. Currently 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 harmonization of monitoring approaches and these should be guided by our understanding of harm in relation to specific types and sources of microplastic (*143*) (section Ecological impacts and risks and section Understanding the risks of microplastics to human health), as well as to assess the efficacy of any interventions adopted.

Human decisions and actions as causes and solutions of microplastics pollution

Scientific publications on sources, and ecological and human health effects of microplastics outline current 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, social and behavioral sciences can make important contributions here (*144*).

Why did plastic materials and products become so successful in the first place? Developed by chemists in the 19th/20th century, writers (*145*) in the 1930s speculated that these new materials might even reduce global conflict (*145*). Widescale 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 as *The Graduate* (1967) (*146*), 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 current practices of plastic production, use and disposal have been presented (*120*) (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 (section Ecological impacts and risks and section 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 s(*144*, *148*). Public concern about plastic in the ocean recently ranked higher than concern about climate change in both Australia and the US (*149*, *150*); while Europeans and Australians regarded plastic pollution as the biggest marine related threat to human health, followed by chemical/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 impacting 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, strong public support for policy measures against plastic pollution has recently been shown [e.g., (*158*) in a Swedish sample]. Overall, public opinion data indicates concern and a desire for action.

Which actions should be prioritized (*159*)? As with all "wicked" problems, no single action will suffice, concerted efforts and consensus between different actor groups are required. 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, accounting 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*); section Ecological impacts and risks and section Understanding the risks of microplastics to human health]? The precautionary principle (*83*, *84*) aims at preventing harm where early warnings about hazards exist, especially in light of 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 for establishing evidence of harm and risk of microplastics, but also for obtaining solid evidence on associated socio-political 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 UN draft global agreement (*53*) recognized microplastics as a key aspect of plastic pollution, along with plastics materials and products and plastic related chemicals (preamble). The challenge, however, will lie in the detail of how to address the multiple sources and pathways for microplastic (section Sources, transport, distribution, and environmental concentrations of microplastics).

Regulating and monitoring primary microplastics that are manufactured ≤5mm 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 the European Economic Area (EEA), which has 30 member countries (*174*); and in 2023 the EU chemical legislation REACH expanded this ban to all products containing intentionally added microplastics (*175*). The draft global agreement (*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 where microplastics are "intentionally added" to products. An additional major upstream source of primary microplastic pollution is spillage, during transportation, of pre-production pellets, powders and flakes that are used to manufacture plastic products. Here regulations on transportation by the IMO under the International Maritime Dangerous Goods Code(s) (IMDG) and required disclosure by insurance companies could be effective; but need to include pre-production materials of all sizes not just those <5mm. 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.

Secondary microplastics are more complex to regulate. Apart from legislation on Oxo-degradable plastics, which have been banned in the US and EU in recognition of their breakdown into microplastics (*176*), most regulations (Fig. 1) have targeted mitigation post generation. For example, washing machine filters to capture microfibers 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 containing 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 eco-modulated taxes based on release rates. For example, better design of yarns and textiles could substantially (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 UV 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 FAO voluntary code of conduct (*177*), under development for adoption in 2024. Consideration must also be given to an ambiguity in the Treaty text 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 agreement releases of secondary microplastics originating 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, section Outlook and evidence needs). Some countries have suggested reduction of secondary microplastic releases could be incorporated under measures for product design, composition and performance (Part II.5), aiming to address the safety, durability, reusability, refillability, repairability and refurbishability of products generally. Ensuring product safety will require strong regulation of chemicals and polymers of concern used in plastics, as proposed in Part II.2 of the draft agreement; and assessment should start by considering the essentiality of problematic products, associated chemicals and microplastics (*178*).

Secondary microplastics resulting from breakdown of macroplastics in the environment (Fig. 1) are best addressed via measures to minimize release of macroplastics to the environment in the first place. This includes reducing production, improving product design and promoting non-plastic 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 clean-up devices can harm marine life (*179*, *180*), emphasizing the critical importance of independently evaluating any potential intervention across a range of societal context prior to it being adopted (*181*).

Based on existing legislation and diversity of sources and pathways for microplastics to enter the environment a range of measures will be needed (Fig. 1) taking a sectoral approach considering regional differences in essentiality and waste management infrastructure. Key requirements for the success under the Global Plastic Treaty are baselines and targets to reduce production and consumption as well safety, sustainability and essentiality criteria relating to the life cycle of plastic products and the chemicals they contain (*182*); together with measures to ensure a just transition, for example in relation to the livelihoods of wase 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 twenty years of research focused specifically on microplastics, there is extensive evidence of substantial widescale environmental accumulation (Fig. 2). Toxicological effects have been confirmed across all levels of biological organization (Fig. 3); there is evidence of potential effects on human health (Fig. 4) together with 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, 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 together with consideration of the relevant socio-technical and geographic context. In our view, science will be just as important guiding the way toward solutions as it has been in identifying the problems. The UN Plastic Pollution Treaty now brings tangible opportunity for international actions. The evidence summarized in this review emphasizes that while measures on macroplastic are of critical importance, these alone will be insufficient to address the multitude of sources outlined above (section Sources, transport, distribution, and environmental concentrations of microplastics) and dedicated provisions on microplastic pollution will be essential.

REFERENCES AND NOTES

1. P. G. Ryan, C. L. Moloney, Marine litter keeps increasing. *Nature* **361**, 23 (1993). doi:10.1038/361023a0
2. M. R. Gregory, P. G. Ryan, "Plastic debris and other seabourne persistent debris" in *Marine Debris*, J. M. Coe, D. B. Rogers, Eds. (Springer, 1996), pp. 49–69.
3. J. B. Buchanan, Pollution by synthetic fibres. *Mar. Pollut. Bull.* **2**, 23 (1971). doi:10.1016/0025-326X(71)90136-6
4. E. J. Carpenter, K. L. Smith Jr., Plastics on the Sargasso sea surface. *Science* **175**, 1240–1241 (1972). doi:10.1126/science.175.4027.1240 Medline
5. J. B. Colton Jr., B. R. Burns, F. D. Knapp, Plastic particles in surface waters of the northwestern Atlantic. *Science* **185**, 491–497 (1974). doi:10.1126/science.185.4150.491 Medline
6. E. J. Carpenter, S. J. Anderson, G. R. Harvey, H. P. Miklas, B. B. Peck, Polystyrene spherules in coastal waters. *Science* **178**, 749–750 (1972). doi:10.1126/science.178.4062.749 Medline
7. P. G. Ryan, The characteristics and distribution of plastic particles at the sea-surface off the southwestern Cape Province, South Africa. *Mar. Environ. Res.* **25**, 249–273 (1988). doi:10.1016/0141-1136(88)90015-3
8. R. C. Thompson, Y. Olsen, R. P. Mitchell, A. Davis, S. J. Rowland, A. W. G. John, D. McGonigle, A. E. Russell, Lost at sea: Where is all the plastic? *Science* **304**, 838 (2004). doi:10.1126/science.1094559 Medline
9. P. G. Ryan, "A brief history of marine litter research" in *Marine Anthropogenic Litter*, M. Bergmann, L. Gutow, M. Klages, Eds. (Springer, 2015), pp. 1–25.
10. N. B. Hartmann, T. Hüffer, R. C. Thompson, M. Hassellöv, A. Verschoor, A. E. Daugaard, S. Rist, T. Karlsson, N. Brennholt, M. Cole, M. P. Herrling, M. C. Hess, N. P. Ivleva, A. L. Lusher, M. Wagner, Are we speaking the same language? Recommendations for a definition and categorization framework for plastic debris. *Environ. Sci. Technol.* **53**, 1039–1047 (2019). doi:10.1021/acs.est.8b05297 Medline
11. C. Arthur, J. Baker, H. Bamford, Eds., *Proceedings of the International Research Workshop on the Occurrence, Effects, and Fate of Microplastic Marine Debris* (NOAA Technical Memorandum NOS-OR&R-48, 2009).
12. European Parliament, "Directive 2008/56/EC establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive)" (2008).
13. J. Boucher, D. Friot, "Primary microplastics in the oceans: A global evaluation of sources" (IUCN, 2017).
14. Pew Charitable Trust, "Breaking the plastic wave" (Pew Charitable Trust, 2020).
15. P. Paruta, M. Pucino, J. Boucher, "Plastic paints the environment" (Environmental Action, 2021).
16. GESAMP, "Sources, fate and effects of microplastics in the marine environment: A global assessment," P. J. Kershaw, Ed. (Reports and Studies GESAMP 90, International Maritime Organization, 2015).
17. GESAMP, "Sources, fate and effects of microplastics in the marine environment: Part two of a global assessment," P. J. Kershaw, C. M. Rochman, Eds. (Reports and Studies GESAMP 93, International Maritime Organization, 2016).
18. M. A. Browne, P. Crump, S. J. Niven, E. Teuten, A. Tonkin, T. Galloway, R. Thompson, Accumulation of microplastic on shorelines woldwide: Sources and sinks. *Environ. Sci. Technol.* **45**, 9175–9179 (2011). doi:10.1021/es201811s Medline
19. L. C. Woodall, A. Sanchez-Vidal, M. Canals, G. L. J. Paterson, R. Coppock, V. Sleight, A. Calafat, A. D. Rogers, B. E. Narayanaswamy, R. C. Thompson, The deep sea is a major sink for microplastic debris. *R. Soc. Open Sci.* **1**, 140317 (2014). doi:10.1098/rsos.140317 Medline
20. M. B. Tekman, C. Wekerle, C. Lorenz, S. Primpke, C. Hasemann, G. Gerdts, M. Bergmann, Tying up loose ends of microplastic pollution in the arctic: Distribution from the sea surface through the water column to deep-sea sediments at the HAUSGARTEN Observatory. *Environ. Sci. Technol.* **54**, 4079–4090 (2020). doi:10.1021/acs.est.9b06981 Medline
21. R. W. Obbard, S. Sadri, Y. Q. Wong, A. A. Khitun, I. Baker, R. C. Thompson, Global warming releases microplastic legacy frozen in Arctic Sea ice. *Earths Futur.* **2**, 315–320 (2014). doi:10.1002/2014EF000240
22. J. A. van Franeker, C. Blaize, J. Danielsen, K. Fairclough, J. Gollan, N. Guse, P.-L. Hansen, M. Heubeck, J.-K. Jensen, G. Le Guillou, B. Olsen, K.-O. Olsen, J. Pedersen, E. W. M. Stienen, D. M. Turner, Monitoring plastic ingestion by the northern fulmar Fulmarus glacialis in the North Sea. *Environ. Pollut.* **159**, 2609–2615 (2011). doi:10.1016/j.envpol.2011.06.008 Medline
23. R. G. Santos, G. E. Machovsky-Capuska, R. Andrades, Plastic ingestion as an evolutionary trap: Toward a holistic understanding. *Science* **373**, 56–60 (2021). doi:10.1126/science.abh0945 Medline
24. A. A. Horton, A. Walton, D. J. Spurgeon, E. Lahive, C. Svendsen, Microplastics in freshwater and terrestrial environments: Evaluating the current understanding to identify the knowledge gaps and future research priorities. *Sci. Total Environ.* **586**, 127–141 (2017). doi:10.1016/j.scitotenv.2017.01.190 Medline
25. M. Eriksen, S. Mason, S. Wilson, C. Box, A. Zellers, W. Edwards, H. Farley, S. Amato, Microplastic pollution in the surface waters of the Laurentian Great Lakes. *Mar. Pollut. Bull.* **77**, 177–182 (2013). doi:10.1016/j.marpolbul.2013.10.007 Medline
26. C. M. Rochman, Microplastics research-from sink to source. *Science* **360**, 28–29 (2018). doi:10.1126/science.aar7734 Medline
27. F. Büks, M. Kaupenjohann, Global concentrations of microplastics in soils - a review. *Soil* **6**, 649–662 (2020). doi:10.5194/soil-6-649-2020
28. I. E. Napper, B. F. R. Davies, H. Clifford, S. Elvin, H. J. Koldewey, P. A. Mayewski, K. R. Miner, M. Potocki, A. C. Elmore, A. P. Gajurel, R. C. Thompson, Reaching new

heights in plastic pollution—Preliminary findings of microplastics on Mount Everest. *One Earth* **3**, 621–630 (2020). doi:10.1016/j.oneear.2020.10.020
29. R. Dris, J. Gasperi, M. Saad, C. Mirande, B. Tassin, Synthetic fibers in atmospheric fallout: A source of microplastics in the environment? *Mar. Pollut. Bull.* **104**, 290–293 (2016). doi:10.1016/j.marpolbul.2016.01.006 Medline
30. S. L. Wright, J. Ulke, A. Font, K. L. A. Chan, F. J. Kelly, Atmospheric microplastic deposition in an urban environment and an evaluation of transport. *Environ. Int.* **136**, 105411 (2020). doi:10.1016/j.envint.2019.105411 Medline
31. M. R. Gregory, Plastic scrubbers' in hand cleansers: A further (and minor) source for marine pollution identified. *Mar. Pollut. Bull.* **32**, 867–871 (1996). doi:10.1016/S0025-326X(96)00047-1
32. M. R. Gregory, Plastic pellets on New Zealand beaches. *Mar. Pollut. Bull.* **8**, 82–84 (1977). doi:10.1016/0025-326X(77)90193-X
33. D. T. Tudor, A. T. Williams, "Investigation of litter problems in the Severn Estuary/Bristol Channel area" (R&D Technical Report E1-082/TR, Environment Agency, 2001).
34. UN Environment Programme (UNEP), "Mapping of global plastics value chain and plastics losses to the environment; With a particular focus on marine environment" (UNEP, 2018).
35. T. Hofmann, S. Ghoshal, N. Tufenkji, J. F. Adamowski, S. Bayen, Q. Chen, P. Demokritou, M. Flury, T. Hüffer, N. P. Ivleva, R. Ji, R. L. Leask, M. Maric, D. M. Mitrano, M. Sander, S. Pahl, M. C. Rillig, T. R. Walker, J. C. White, K. J. Wilkinson, Plastics can be used more sustainably in agriculture. *Commun. Earth Environ.* **4**, 332 (2023). doi:10.1038/s43247-023-00982-4
36. G. Suzuki, N. Uchida, K. Tanaka, O. Higashi, Y. Takahashi, H. Kuramochi, N. Yamaguchi, M. Osako, Global discharge of microplastics from mechanical recycling of plastic waste. *Environ. Pollut.* **348**, 123855 (2024). doi:10.1016/j.envpol.2024.123855 Medline
37. D. Armada, M. Llompart, M. Celeiro, P. Garcia-Castro, N. Ratola, T. Dagnac, J. de Boer, Global evaluation of the chemical hazard of recycled tire crumb rubber employed on worldwide synthetic turf football pitches. *Sci. Total Environ.* **812**, 152542 (2022). doi:10.1016/j.scitotenv.2021.152542 Medline
38. SAPEA, *A Scientific Perspective on Microplastics in Nature and Society* (2019).
39. R. Thompson, C. Moore, A. Andrady, M. Gregory, H. Takada, S. Weisberg, New directions in plastic debris. *Science* **310**, 1117 (2005). doi:10.1126/science.310.5751.1117b Medline
40. SAPEA, "Biodegradability of plastics in the open environment" (Publications Office of the European Union, 2021).
41. C. Lassen, S. F. Hansen, K. Magnusson, N. B. Hartmann, P. Rehne Jensen, T. G. Nielsen, A. Brinch, D. E. P. Agency, "Microplastics: Occurrence, effects and sources of releases to the environment in Denmark" (Danish Environmental Protection Agency, 2015).
42. K. Magnusson, K. Eliaeson, A. Fråne, K. Haikonen, M. Olshammar, J. Stadmark, J. Hultén, S. E. R. Institute, "Swedish sources and pathways for microplastics to the marine environment" (2016).
43. J. R. Jambeck, R. Geyer, C. Wilcox, T. R. Siegler, M. Perryman, A. Andrady, R. Narayan, K. L. Law, Plastic waste inputs from land into the ocean. *Science* **347**, 768–771 (2015). doi:10.1126/science.1260352 Medline
44. W. W. Y. Lau, Y. Shiran, R. M. Bailey, E. Cook, M. R. Stuchtey, J. Koskella, C. A. Velis, L. Godfrey, J. Boucher, M. B. Murphy, R. C. Thompson, E. Jankowska, A. Castillo Castillo, T. D. Pilditch, B. Dixon, L. Koerselman, E. Kosior, E. Favoino, J. Gutberlet, S. Baulch, M. E. Atreya, D. Fischer, K. K. He, M. M. Petit, U. R. Sumaila, E. Neil, M. V. Bernhofen, K. Lawrence, J. E. Palardy, Evaluating scenarios toward zero plastic pollution. *Science* **369**, 1455–1461 (2020). doi:10.1126/science.aba9475 Medline
45. Earth Action, "Leakage of microplastics into oceans and land" (Earth Action, 2023).
46. A. Cózar, F. Echevarría, J. I. González-Gordillo, X. Irigoien, B. Ubeda, S. Hernández-León, A. T. Palma, S. Navarro, J. García-de-Lomas, A. Ruiz, M. L. Fernández-de-Puelles, C. M. Duarte, Plastic debris in the open ocean. *Proc. Natl. Acad. Sci. U.S.A.* **111**, 10239–10244 (2014). doi:10.1073/pnas.1314705111 Medline
47. E. van Sebille, C. Wilcox, L. Lebreton, N. Maximenko, B. D. Hardesty, J. A. van Franeker, M. Eriksen, D. Siegel, F. Galgani, K. L. Law, A global inventory of small floating plastic debris. *Environ. Res. Lett.* **10**, 124006 (2015). doi:10.1088/1748-9326/10/12/124006
48. K. Enders, R. Lenz, C. A. Stedmon, T. G. Nielsen, Abundance, size and polymer composition of marine microplastics ≥10μm in the Atlantic Ocean and their modelled vertical distribution. *Mar. Pollut. Bull.* **100**, 70–81 (2015). doi:10.1016/j.marpolbul.2015.09.027 Medline
49. F. De Falco, M. Cocca, M. Avella, R. C. Thompson, Microfiber release to water, via laundering, and to air, via everyday use: A comparison between polyester clothing with differing textile parameters. *Environ. Sci. Technol.* **54**, 3288–3296 (2020). doi:10.1021/acs.est.9b06892 Medline
50. N. Evangeliou, H. Grythe, Z. Klimont, C. Heyes, S. Eckhardt, S. Lopez-Aparicio, A. Stohl, Atmospheric transport is a major pathway of microplastics to remote regions. *Nat. Commun.* **11**, 3381 (2020). doi:10.1038/s41467-020-17201-9 Medline
51. L. M. Werbowski, A. N. Gilbreath, K. Munno, X. Zhu, J. Grbic, T. Wu, R. Sutton, M. D. Sedlak, A. D. Deshpande, C. M. Rochman, Urban stormwater runoff: A major pathway for anthropogenic particles, black rubbery fragments, and other types of microplastics to urban receiving waters. *ACS ES T Water* **1**, 1420–1428 (2021). doi:10.1021/acsestwater.1c00017
52. D. Harley-Nyang, F. A. Memon, A. Osorio Baquero, T. Galloway, Variation in microplastic concentration, characteristics and distribution in sewage sludge and biosolids around the world. *Sci. Total Environ.* **891**, 164068 (2023). doi:10.1016/j.scitotenv.2023.164068
53. United Nations Environment Programme (UNEP), "Revised draft text of the international legally binding instrument on plastic pollution, including in the marine environment" (2023).
54. M. Bergmann, V. Wirzberger, T. Krumpen, C. Lorenz, S. Primpke, M. B. Tekman, G. Gerdts, High quantities of microplastic in Arctic deep-sea sediments from the HAUSGARTEN observatory. *Environ. Sci. Technol.* **51**, 11000–11010 (2017). doi:10.1021/acs.est.7b03331 Medline
55. M. Kooi, A. A. Koelmans, Simplifying microplastic via continuous probability distributions for size, shape and density. *Environ. Sci. Technol. Lett.* **6**, 551–557 (2019). doi:10.1021/acs.estlett.9b00379
56. Y. Mato, T. Isobe, H. Takada, H. Kanehiro, C. Ohtake, T. Kaminuma, Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. *Environ. Sci. Technol.* **35**, 318–324 (2001). doi:10.1021/es0010498 Medline
57. E. L. Teuten, J. M. Saquing, D. R. U. Knappe, M. A. Barlaz, S. Jonsson, A. Björn, S. J. Rowland, R. C. Thompson, T. S. Galloway, R. Yamashita, D. Ochi, Y. Watanuki, C. Moore, P. H. Viet, T. S. Tana, M. Prudente, R. Boonyatumanond, M. P. Zakaria, K. Akkhavong, Y. Ogata, H. Hirai, S. Iwasa, K. Mizukawa, Y. Hagino, A. Imamura, M. Saha, H. Takada, Transport and release of chemicals from plastics to the environment and to wildlife. *Philos. Trans. R. Soc. London Ser. B* **364**, 2027–2045 (2009). doi:10.1098/rstb.2008.0284 Medline
58. S. Kühn, J. A. van Franeker, Quantitative overview of marine debris ingested by marine megafauna. *Mar. Pollut. Bull.* **151**, 110858 (2020). doi:10.1016/j.marpolbul.2019.110858 Medline
59. A. A. Koelmans, N. H. Mohamed Nor, E. Hermsen, M. Kooi, S. M. Mintenig, J. De France, Microplastics in freshwaters and drinking water: Critical review and assessment of data quality. *Water Res.* **155**, 410–422 (2019). doi:10.1016/j.watres.2019.02.054 Medline
60. P. E. Redondo-Hasselerharm, A. Rico, E. Huerta Lwanga, C. A. M. van Gestel, A. A. Koelmans, Source-specific probabilistic risk assessment of microplastics in soils applying quality criteria and data alignment methods. *J. Hazard. Mater.* **467**, 133732 (2024). doi:10.1016/j.jhazmat.2024.133732 Medline
61. Z. L. R. Botterell, N. Beaumont, T. Dorrington, M. Steinke, R. C. Thompson, P. K. Lindeque, Bioavailability and effects of microplastics on marine zooplankton: A review. *Environ. Pollut.* **245**, 98–110 (2019). doi:10.1016/j.envpol.2018.10.065 Medline
62. G. Everaert, L. Van Cauwenberghe, M. De Rijcke, A. A. Koelmans, J. Mees, M. Vandegehuchte, C. R. Janssen, Risk assessment of microplastics in the ocean: Modelling approach and first conclusions. *Environ. Pollut.* **242**, 1930–1938 (2018). doi:10.1016/j.envpol.2018.07.069 Medline
63. C. Edo, A. R. Fernández-Alba, F. Vejsnæs, J. J. M. van der Steen, F. Fernández-Piñas, R. Rosal, Honeybees as active samplers for microplastics. *Sci. Total Environ.* **767**, 144481 (2021). doi:10.1016/j.scitotenv.2020.144481 Medline
64. C. J. Foley, Z. S. Feiner, T. D. Malinich, T. O. Höök, A meta-analysis of the effects of exposure to microplastics on fish and aquatic invertebrates. *Sci. Total Environ.* **631–632**, 550–559 (2018). doi:10.1016/j.scitotenv.2018.03.046 Medline

65. T. Kögel, Ø. Bjorøy, B. Toto, A. M. Bienfait, M. Sanden, Micro- and nanoplastic toxicity on aquatic life: Determining factors. *Sci. Total Environ.* **709**, 136050 (2020). doi:10.1016/j.scitotenv.2019.136050 Medline
66. V. N. de Ruijter, P. E. Redondo-Hasselerharm, T. Gouin, A. A. Koelmans, Quality criteria for microplastic effect studies in the context of risk assessment: A critical review. *Environ. Sci. Technol.* **54**, 11692–11705 (2020). doi:10.1021/acs.est.0c03057 Medline
67. Z. Tian, H. Zhao, K. T. Peter, M. Gonzalez, J. Wetzel, C. Wu, X. Hu, J. Prat, E. Mudrock, R. Hettinger, A. E. Cortina, R. G. Biswas, F. V. C. Kock, R. Soong, A. Jenne, B. Du, F. Hou, H. He, R. Lundeen, A. Gilbreath, R. Sutton, N. L. Scholz, J. W. Davis, M. C. Dodd, A. Simpson, J. K. McIntyre, E. P. Kolodziej, A ubiquitous tire rubber-derived chemical induces acute mortality in coho salmon. *Science* **371**, 185–189 (2021). doi:10.1126/science.abd6951 Medline
68. S. Stevens, M. McPartland, Z. Bartosova, H. S. Skåland, J. Völker, M. Wagner, Plastic food packaging from five countries contains endocrine- and metabolism-disrupting chemicals. *Environ. Sci. Technol.* **58**, 4859–4871 (2024). doi:10.1021/acs.est.3c08250 Medline
69. M. A. Browne, A. Dissanayake, T. S. Galloway, D. M. Lowe, R. C. Thompson, Ingested microscopic plastic translocates to the circulatory system of the mussel, *Mytilus edulis* (L.). *Environ. Sci. Technol.* **42**, 5026–5031 (2008). doi:10.1021/es800249a Medline
70. L. M. Thornton Hampton, S. M. Brander, S. Coffin, M. Cole, L. Hermabessiere, A. A. Koelmans, C. M. Rochman, Characterizing microplastic hazards: Which concentration metrics and particle characteristics are most informative for understanding toxicity in aquatic organisms? *Microplast. Nanoplast.* **2**, 20 (2022). doi:10.1186/s43591-022-00040-4
71. R. Lohmann, Microplastics are not important for the cycling and bioaccumulation of organic pollutants in the oceans: But should microplastics be considered POPs themselves? *Integr. Environ. Assess. Manag.* **13**, 460–465 (2017). doi:10.1002/ieam.1914 Medline
72. A. A. Koelmans, A. Bakir, G. A. Burton, C. R. Janssen, Microplastic as a vector for chemicals in the aquatic environment: Critical review and model-supported reinterpretation of empirical studies. *Integr. Environ. Assess. Manag.* **50**, 3315–3326 (2016). doi:10.1021/acs.est.5b06069 Medline
73. A. A. Koelmans, N. J. Diepens, N. H. Mohamed Nor, "Weight of evidence for the microplastic vector effect in the context of chemical risk assessment" in *Microplastic in the Environment: Pattern and Process*, Environmental Contamination Remediation and Management, M. S. Bank, Ed. (Springer, 2022), pp. 155–197.
74. P. Boisseaux, C. Rauert, P. Dewapriya, M.-L. Delignette-Muller, R. Barrett, L. Durndell, F. Pohl, R. Thompson, K. V. Thomas, T. Galloway, Deep dive into the chronic toxicity of tyre particle mixtures and their leachates. *J. Hazard. Mater.* **466**, 133580 (2024). doi:10.1016/j.jhazmat.2024.133580 Medline
75. GESAMP, *Proceedings of the GESAMP International Workshop on Assessing the Risks Associated with Plastics and Microplastics in the Marine Environment*, P. J. Kershaw, B. Carney Almroth, P. Villarrubia-Gómez, A. A. Koelmans, T. Gouin, Eds. (Reports and Studies 103, UNEP, 2020).
76. K. A. Connors, S. D. Dyer, S. E. Belanger, Advancing the quality of environmental microplastic research. *Environ. Toxicol. Chem.* **36**, 1697–1703 (2017). doi:10.1002/etc.3829 Medline
77. L. M. Thornton Hampton, H. Bouwmeester, S. M. Brander, S. Coffin, M. Cole, L. Hermabessiere, A. C. Mehinto, E. Miller, C. M. Rochman, S. B. Weisberg, Research recommendations to better understand the potential health impacts of microplastics to humans and aquatic ecosystems. *Microplast. Nanoplast.* **2**, 18 (2022). doi:10.1186/s43591-022-00038-y
78. V. N. de Ruijter, M. Hof, P. Kotorou, J. van Leeuwen, M. J. van den Heuvel-Greve, I. Roessink, A. A. Koelmans, Microplastic effect tests should use a standard heterogeneous mixture: Multifarious impacts among 16 benthic invertebrate species detected under ecologically relevant test conditions. *Environ. Sci. Technol.* **57**, 19430–19441 (2023). doi:10.1021/acs.est.3c06829 Medline
79. A. A. Koelmans, P. E. Redondo-Hasselerharm, N. H. Mohamed Nor, M. Kooi, Solving the nonalignment of methods and approaches used in microplastic research to consistently characterize risk. *Environ. Sci. Technol.* **54**, 12307–12315 (2020). doi:10.1021/acs.est.0c02982 Medline
80. A. C. Mehinto, S. Coffin, A. A. Koelmans, S. M. Brander, M. Wagner, L. M. Thornton Hampton, A. G. Burton Jr., E. Miller, T. Gouin, S. B. Weisberg, C. M. Rochman, Risk-based management framework for microplastics in aquatic ecosystems. *Microplast. Nanoplast.* **2**, 17 (2022). doi:10.1186/s43591-022-00033-3
81. S. Coffin, S. B. Weisberg, C. Rochman, M. Kooi, A. A. Koelmans, Risk characterization of microplastics in San Francisco Bay, California. *Microplast. Nanoplast.* **2**, 19 (2022). doi:10.1186/s43591-022-00037-z
82. L. Wang, W.-M. Wu, N. S. Bolan, D. C. W. Tsang, Y. Li, M. Qin, D. Hou, Environmental fate, toxicity and risk management strategies of nanoplastics in the environment: Current status and future perspectives. *J. Hazard. Mater.* **401**, 123415 (2021). doi:10.1016/j.jhazmat.2020.123415 Medline
83. C. M. Rochman, A.-M. Cook, A. A. Koelmans, Plastic debris and policy: Using current scientific understanding to invoke positive change. *Environ. Toxicol. Chem.* **35**, 1617–1626 (2016). doi:10.1002/etc.3408 Medline
84. D. Gee, P. Grandjean, S. F. Hansen, M. MacGarvin, J. Martin, G. Nielsen, D. Quist, D. Stanners, "Late lessons from early warnings: science, precaution, innovation" (EEA Report No. 1/2013, European Environment Agency, 2013).
85. S. L. Wright, F. J. Kelly, Plastic and human health: A micro issue? *Environ. Sci. Technol.* **51**, 6634–6647 (2017). doi:10.1021/acs.est.7b00423 Medline
86. N. H. Mohamed Nor, M. Kooi, N. J. Diepens, A. A. Koelmans, Lifetime accumulation of microplastic in children and adults. *Environ. Sci. Technol.* **55**, 5084–5096 (2021). doi:10.1021/acs.est.0c07384 Medline
87. K. D. Cox, G. A. Covernton, H. L. Davies, J. F. Dower, F. Juanes, S. E. Dudas, Human consumption of microplastics. *Environ. Sci. Technol.* **53**, 7068–7074 (2019). doi:10.1021/acs.est.9b01517 Medline
88. A. L. Lusher, M. McHugh, R. C. Thompson, Occurrence of microplastics in the gastrointestinal tract of pelagic and demersal fish from the English Channel. *Mar. Pollut. Bull.* **67**, 94–99 (2013). doi:10.1016/j.marpolbul.2012.11.028 Medline
89. World Health Organization (WHO), "Microplastics in drinking-water" (WHO, 2019).
90. A. I. Catarino, V. Macchia, W. G. Sanderson, R. C. Thompson, T. B. Henry, Low levels of microplastics (MP) in wild mussels indicate that MP ingestion by humans is minimal compared to exposure via household fibres fallout during a meal. *Environ. Pollut.* **237**, 675–684 (2018). doi:10.1016/j.envpol.2018.02.069 Medline
91. World Health Organization (WHO), "Dietary and inhalation exposure to nano- and microplastic particles and potential implications for human health" (WHO, 2022).
92. M. Pletz, Ingested microplastics: Do humans eat one credit card per week? *J. Hazard. Mater. Lett.* **3**, 100071 (2022). doi:10.1016/j.hazl.2022.100071
93. Y. Li, L. Tao, Q. Wang, F. Wang, G. Li, M. Song, Potential health impact of microplastics: A review of environmental distribution, human exposure, and toxic effects. *Environ. Health* **1**, 249–257 (2023). doi:10.1021/envhealth.3c00052
94. G. Sorci, C. Loiseau, Should we worry about the accumulation of microplastics in human organs? *EBioMedicine* **82**, 104191 (2022). doi:10.1016/j.ebiom.2022.104191 Medline
95. S. Abbasi, A. Turner, Human exposure to microplastics: A study in Iran. *J. Hazard. Mater.* **403**, 123799 (2021). doi:10.1016/j.jhazmat.2020.123799 Medline
96. S. Huang, X. Huang, R. Bi, Q. Guo, X. Yu, Q. Zeng, Z. Huang, T. Liu, H. Wu, Y. Chen, J. Xu, Y. Wu, P. Guo, Detection and analysis of microplastics in human sputum. *Environ. Sci. Technol.* **56**, 2476–2486 (2022). doi:10.1021/acs.est.1c03859 Medline
97. P. Schwabl, S. Köppel, P. Königshofer, T. Bucsics, M. Trauner, T. Reiberger, B. Liebmann, Detection of various microplastics in human stool: A prospective case series. *Ann. Intern. Med.* **171**, 453–457 (2019). doi:10.7326/M19-0618 Medline
98. A. Ragusa, A. Svelato, C. Santacroce, P. Catalano, V. Notarstefano, O. Carnevali, F. Papa, M. C. A. Rongioletti, F. Baiocco, S. Draghi, E. D'Amore, D. Rinaldo, M. Matta, E. Giorgini, Plasticenta: First evidence of microplastics in human placenta. *Environ. Int.* **146**, 106274 (2021). doi:10.1016/j.envint.2020.106274 Medline
99. H. A. Leslie, M. J. M. van Velzen, S. H. Brandsma, A. D. Vethaak, J. J. Garcia-Vallejo, M. H. Lamoree, Discovery and quantification of plastic particle pollution in human blood. *Environ. Int.* **163**, 107199 (2022). doi:10.1016/j.envint.2022.107199 Medline
100. T. Horvatits, M. Tamminga, B. Liu, M. Sebode, A. Carambia, L. Fischer, K. Püschel, S. Huber, E. K. Fischer, Microplastics detected in cirrhotic liver tissue. *EBioMedicine* **82**, 104147 (2022). doi:10.1016/j.ebiom.2022.104147 Medline
101. S. Liu, J. Guo, X. Liu, R. Yang, H. Wang, Y. Sun, B. Chen, R. Dong, Detection of various microplastics in placentas, meconium, infant feces, breastmilk and infant formula: A pilot prospective study. *Sci. Total Environ.* **854**, 158699 (2023).

doi:10.1016/j.scitotenv.2022.158699 Medline
102. J. M. Rotchell, L. C. Jenner, E. Chapman, R. T. Bennett, I. O. Bolanle, M. Loubani, L. Sadofsky, T. M. Palmer, Detection of microplastics in human saphenous vein tissue using μFTIR: A pilot study. *PLOS ONE* **18**, e0280594 (2023). doi:10.1371/journal.pone.0280594 Medline
103. L. Zhu, J. Zhu, R. Zuo, Q. Xu, Y. Qian, L. An, Identification of microplastics in human placenta using laser direct infrared spectroscopy. *Sci. Total Environ.* **856**, 159060 (2023). doi:10.1016/j.scitotenv.2022.159060 Medline
104. C. Baeza-Martínez, S. Olmos, M. González-Pleiter, J. López-Castellanos, E. García-Pachón, M. Masiá-Canuto, L. Hernández-Blasco, J. Bayo, First evidence of microplastics isolated in European citizens' lower airway. *J. Hazard. Mater.* **438**, 129439 (2022). doi:10.1016/j.jhazmat.2022.129439 Medline
105. L. C. Jenner, J. M. Rotchell, R. T. Bennett, M. Cowen, V. Tentzeris, L. R. Sadofsky, Detection of microplastics in human lung tissue using μFTIR spectroscopy. *Sci. Total Environ.* **831**, 154907 (2022). doi:10.1016/j.scitotenv.2022.154907 Medline
106. Y. S. Ibrahim, S. Tuan Anuar, A. A. Azmi, W. M. A. Wan Mohd Khalik, S. Lehata, S. R. Hamzah, D. Ismail, Z. F. Ma, A. Dzulkarnaen, Z. Zakaria, N. Mustaffa, S. E. Tuan Sharif, Y. Y. Lee, Detection of microplastics in human colectomy specimens. *JGH Open* **5**, 116–121 (2020). doi:10.1002/jgh3.12457 Medline
107. N. Zhang, Y. B. Li, H. R. He, J. F. Zhang, G. S. Ma, You are what you eat: Microplastics in the feces of young men living in Beijing. *Sci. Total Environ.* **767**, 144345 (2021). doi:10.1016/j.scitotenv.2020.144345 Medline
108. Z. Yan, Y. Liu, T. Zhang, F. Zhang, H. Ren, Y. Zhang, Analysis of microplastics in human feces reveals a correlation between fecal microplastics and inflammatory bowel disease status. *Environ. Sci. Technol.* **56**, 414–421 (2022). doi:10.1021/acs.est.1c03924 Medline
109. W. Lu, X. Li, S. Wang, C. Tu, L. Qiu, H. Zhang, C. Zhong, S. Li, Y. Liu, J. Liu, Y. Zhou, New evidence of microplastics in the lower respiratory tract: inhalation through smoking. *Environ. Sci. Technol.* **57**, 8496–8505 (2023). doi:10.1021/acs.est.3c00716 Medline
110. J. C. Prata, Microplastics and human health: Integrating pharmacokinetics. *Crit. Rev. Environ. Sci. Technol.* **53**, 1489–1511 (2023). doi:10.1080/10643389.2023.2195798
111. I. Wardani, N. Hazimah Mohamed Nor, S. L. Wright, I. M. Kooter, A. A. Koelmans, Nano- and microplastic PBK modeling in the context of human exposure and risk assessment. *Environ. Int.* **186**, 108504 (2024). doi:10.1016/j.envint.2024.108504 Medline
112. R. Marfella, F. Prattichizzo, C. Sardu, G. Fulgenzi, L. Graciotti, T. Spadoni, N. D'Onofrio, L. Scisciola, R. La Grotta, C. Frigé, V. Pellegrini, M. Municinò, M. Siniscalchi, F. Spinetti, G. Vigliotti, C. Vecchione, A. Carrizzo, G. Accarino, A. Squillante, G. Spaziano, D. Mirra, R. Esposito, S. Altieri, G. Falco, A. Fenti, S. Galoppo, S. Canzano, F. C. Sasso, G. Matacchione, F. Olivieri, F. Ferraraccio, I. Panarese, P. Paolisso, E. Barbato, C. Lubritto, M. L. Balestrieri, C. Mauro, A. E. Caballero, S. Rajagopalan, A. Ceriello, B. D'Agostino, P. Iovino, G. Paolisso, Microplastics and nanoplastics in atheromas and cardiovascular events. *N. Engl. J. Med.* **390**, 900–910 (2024). doi:10.1056/NEJMoa2309822 Medline
113. A. A. Koelmans, P. E. Redondo-Hasselerharm, N. H. M. Nor, V. N. de Ruijter, S. M. Mintenig, M. Kooi, Risk assessment of microplastic particles. *Nat. Rev. Mater.* **7**, 138–152 (2022). doi:10.1038/s41578-021-00411-y
114. O. Schmid, T. Stoeger, Surface area is the biologically most effective dose metric for acute nanoparticle toxicity in the lung. *J. Aerosol Sci.* **99**, 133–143 (2016). doi:10.1016/j.jaerosci.2015.12.006
115. P. Li, J. Liu, Micro(nano)plastics in the human body: Sources, occurrences, fates, and health risks. *Environ. Sci. Technol.* **58**, 3065–3078 (2024). doi:10.1021/acs.est.3c08902 Medline
116. B. L. M. Fontes, L. C. de Souza e Souza, A. P. S. da Silva de Oliveira, R. N. da Fonseca, M. P. C. Neto, C. R. Pinheiro, The possible impacts of nano and microplastics on human health: Lessons from experimental models across multiple organs. *J. Toxicol. Environ. Health B Crit. Rev.* **27**, 153–187 (2024). doi:10.1080/10937404.2024.2330962 Medline
117. T. Gouin, R. Ellis-Hutchings, L. M. Thornton Hampton, C. L. Lemieux, S. L. Wright, Screening and prioritization of nano- and microplastic particle toxicity studies for evaluating human health risks – development and application of a toxicity study assessment tool. *Microplast. Nanoplast.* **2**, 2 (2022). doi:10.1186/s43591-021-00023-x Medline
118. S. Coffin, H. Bouwmeester, S. Brander, P. Damdimopoulou, T. Gouin, L. Hermabessiere, E. Khan, A. A. Koelmans, C. L. Lemieux, K. Teerds, M. Wagner, S. B. Weisberg, S. Wright, Development and application of a health-based framework for informing regulatory action in relation to exposure of microplastic particles in California drinking water. *Microplast. Nanoplast.* **2**, 12 (2022). doi:10.1186/s43591-022-00030-6 Medline
119. J. Cao, Q. Yang, J. Jiang, T. Dalu, A. Kadushkin, J. Singh, R. Fakhrullin, F. Wang, X. Cai, R. Li, Coronas of micro/nano plastics: A key determinant in their risk assessments. *Part. Fibre Toxicol.* **19**, 55 (2022). doi:10.1186/s12989-022-00492-9 Medline
120. P. J. Landrigan, H. Raps, M. Cropper, C. Bald, M. Brunner, E. M. Canonizado, D. Charles, T. C. Chiles, M. J. Donohue, J. Enck, P. Fenichel, L. E. Fleming, C. Ferrier-Pages, R. Fordham, A. Gozt, C. Griffin, M. E. Hahn, B. Haryanto, R. Hixson, H. Ianelli, B. D. James, P. Kumar, A. Laborde, K. L. Law, K. Martin, J. Mu, Y. Mulders, A. Mustapha, J. Niu, S. Pahl, Y. Park, M.-L. Pedrotti, J. A. Pitt, M. Ruchirawat, B. J. Seewoo, M. Spring, J. J. Stegeman, W. Suk, C. Symeonides, H. Takada, R. C. Thompson, A. Vicini, Z. Wang, E. Whitman, D. Wirth, M. Wolff, A. K. Yousuf, S. Dunlop, The Minderoo-Monaco Commission on Plastics and Human Health. *Ann. Glob. Health* **89**, 23 (2023). doi:10.5334/aogh.4056 Medline
121. H. K. Imhof, J. Schmid, R. Niessner, N. P. Ivleva, C. Laforsch, A novel, highly efficient method for the separation and quantification of plastic particles in sediments of aquatic environments. *Limnol. Oceanogr. Methods* **10**, 524–537 (2012). doi:10.4319/lom.2012.10.524
122. A. Dehaut, A.-L. L. Cassone, L. Frère, L. Hermabessiere, C. Himber, E. Rinnert, G. Rivière, C. Lambert, P. Soudant, A. Huvet, G. Duflos, I. Paul-Pont, Microplastics in seafood: Benchmark protocol for their extraction and characterization. *Environ. Pollut.* **215**, 223–233 (2016). doi:10.1016/j.envpol.2016.05.018 Medline
123. M. Cole, P. Lindeque, E. Fileman, C. Halsband, R. Goodhead, J. Moger, T. S. Galloway, Microplastic ingestion by zooplankton. *Environ. Sci. Technol.* **47**, 6646–6655 (2013). doi:10.1021/es400663f Medline
124. W. Courtene-Jones, B. Quinn, F. Murphy, S. F. Gary, B. E. Narayanaswamy, Optimisation of enzymatic digestion and validation of specimen preservation methods for the analysis of ingested microplastics. *Anal. Methods* **9**, 1437–1445 (2017). doi:10.1039/C6AY02343F
125. A. S. Tagg, J. P. Harrison, Y. Ju-Nam, M. Sapp, E. L. Bradley, C. J. Sinclair, J. J. Ojeda, Fenton's reagent for the rapid and efficient isolation of microplastics from wastewater. *Chem. Commun.* **53**, 372–375 (2017). doi:10.1039/C6CC08798A Medline
126. L. C. Woodall, C. Gwinnett, M. Packer, R. C. Thompson, L. F. Robinson, G. L. J. Paterson, Using a forensic science approach to minimize environmental contamination and to identify microfibres in marine sediments. *Mar. Pollut. Bull.* **95**, 40–46 (2015). doi:10.1016/j.marpolbul.2015.04.044 Medline
127. C. Wesch, A. M. Elert, M. Wörner, U. Braun, R. Klein, M. Paulus, Assuring quality in microplastic monitoring: About the value of clean-air devices as essentials for verified data. *Sci. Rep.* **7**, 5424 (2017). doi:10.1038/s41598-017-05838-4 Medline
128. Y. Zheng, J. Li, C. Sun, W. Cao, M. Wang, F. Jiang, P. Ju, Comparative study of three sampling methods for microplastics analysis in seawater. *Sci. Total Environ.* **765**, 144495 (2021). doi:10.1016/j.scitotenv.2020.144495 Medline
129. A. Ter Halle, L. Ladirat, M. Martignac, A. F. Mingotaud, O. Boyron, E. Perez, To what extent are microplastics from the open ocean weathered? *Environ. Pollut.* **227**, 167–174 (2017). doi:10.1016/j.envpol.2017.04.051 Medline
130. F. De Falco, M. P. Gullo, G. Gentile, E. Di Pace, M. Cocca, L. Gelabert, M. Brouta-Agnésa, A. Rovira, R. Escudero, R. Villalba, R. Mossotti, A. Montarsolo, S. Gavignano, C. Tonin, M. Avella, Evaluation of microplastic release caused by textile washing processes of synthetic fabrics. *Environ. Pollut.* **236**, 916–925 (2018). doi:10.1016/j.envpol.2017.10.057 Medline
131. I. E. Napper, R. C. Thompson, Release of synthetic microplastic plastic fibres from domestic washing machines: Effects of fabric type and washing conditions. *Mar. Pollut. Bull.* **112**, 39–45 (2016). doi:10.1016/j.marpolbul.2016.09.025 Medline
132. V. Hidalgo-Ruz, L. Gutow, R. C. Thompson, M. Thiel, Microplastics in the marine environment: A review of the methods used for identification and quantification. *Environ. Sci. Technol.* **46**, 3060–3075 (2012). doi:10.1021/es2031505 Medline
133. W. Cowger, A. Gray, S. H. Christiansen, H. DeFrond, A. D. Deshpande, L. Hemabessiere, E. Lee, L. Mill, K. Munno, B. E. Ossmann, M. Pittroff, C. Rochman, G. Sarau, S. Tarby, S. Primpke, Critical review of processing and classification

techniques for images and spectra in microplastic research. *Appl. Spectrosc.* **74**, 989–1010 (2020). doi:10.1177/0003702820929064 Medline
134. S. Primpke, M. Wirth, C. Lorenz, G. Gerdts, Reference database design for the automated analysis of microplastic samples based on Fourier transform infrared (FTIR) spectroscopy. *Anal. Bioanal. Chem.* **410**, 5131–5141 (2018). doi:10.1007/s00216-018-1156-x Medline
135. M. Shafi, A. Lodh, M. Khajuria, V. P. Ranjan, K. M. Gani, S. Chowdhury, S. Goel, Are we underestimating stormwater? Stormwater as a significant source of microplastics in surface waters. *J. Hazard. Mater.* **465**, 133445 (2024). doi:10.1016/j.jhazmat.2024.133445 Medline
136. J. V. Miller, J. R. Maskrey, K. Chan, K. M. Unice, Pyrolysis-gas chromatography-mass spectrometry (Py-GC-MS) quantification of tire and road wear particles (TRWP) in environmental matrices: Assessing the importance of microstructure in instrument calibration protocols. *Anal. Lett.* **55**, 1004–1016 (2022). doi:10.1080/00032719.2021.1979994
137. S. M. Mintenig, P. S. Bäuerlein, A. A. Koelmans, S. C. Dekker, A. P. van Wezel, Closing the gap between small and smaller: Towards a framework to analyse nano- and microplastics in aqueous environmental samples. *Environ. Sci. Nano* **5**, 1640–1649 (2018). doi:10.1039/C8EN00186C
138. F. De Falco, T. Nacci, L. Durndell, R. C. Thompson, I. Degano, F. Modugno, A thermoanalytical insight into the composition of biodegradable polymers and commercial products by EGA-MS and Py-GC-MS. *J. Anal. Appl. Pyrolysis* **171**, 105937 (2023). doi:10.1016/j.jaap.2023.105937
139. P. E. Redondo-Hasselerharm, G. Vink, D. M. Mitrano, A. A. Koelmans, Metal-doping of nanoplastics enables accurate assessment of uptake and effects on *Gammarus pulex*. *Environ. Sci. Nano* **8**, 1761–1770 (2021). doi:10.1039/D1EN00068C Medline
140. N. J. Clark, A. C. Fischer, L. Durndell, T. S. Galloway, R. C. Thompson, Translocation of ^{14}C-polystyrene nanoplastics into fish during a very-low concentration dietary exposure. *Chemosphere* **341**, 140058 (2023). doi:10.1016/j.chemosphere.2023.140058 Medline
141. M. Al-Sid-Cheikh, S. J. Rowland, K. Stevenson, C. Rouleau, T. B. Henry, R. C. Thompson, Uptake, whole-body distribution, and depuration of nanoplastics by the scallop *Pecten maximus* at environmentally realistic concentrations. *Environ. Sci. Technol.* **52**, 14480–14486 (2018). doi:10.1021/acs.est.8b05266 Medline
142. Y. Michida, S. Chavanich, S. Chiba, M. R. Cordova, A. Cozar, F. Galgani, P. Hagman, H. Hinata, A. Isobe, P. Kershaw, N. Kozlovskii, L. Daoji, A. Lusher, E. Marti, S. A. Mason, J. Mu, H. Saito, W. J. Shim, A. D. Syakti, H. Takada, R. Thompson, T. Tokai, K. Uchida, K. Vasilenko, J. Wang, "Guidelines for harmonizing ocean surface microplastic monitoring methods" (Ministry of the Environment Japan, 2020).
143. C. M. Rochman, F. Regan, R. C. Thompson, On the harmonization of methods for measuring the occurrence, fate and effects of microplastics. *Anal. Methods* **9**, 1324–1325 (2017). doi:10.1039/C7AY90014G
144. S. Pahl, K. J. Wyles, The human dimension: How social and behavioural research methods can help address microplastics in the environment. *Anal. Methods* **9**, 1404–1411 (2017). doi:10.1039/C6AY02647H
145. V. E. Yarsley, E. G. Couzens, *Plastics in the Service of Man* (Penguin, 1956).
146. J. L. Meikle, *American Plastic: A Cultural History* (Rutgers Univ. Press, 1995).
147. L. M. Heidbreder, I. Bablok, S. Drews, C. Menzel, Tackling the plastic problem: A review on perceptions, behaviors, and interventions. *Sci. Total Environ.* **668**, 1077–1093 (2019). doi:10.1016/j.scitotenv.2019.02.437 Medline
148. K. Syberg, S. F. Hansen, T. B. Christensen, F. R. Khan, "Risk perception of plastic pollution: Importance of stakeholder involvement and citizen science" in *Freshwater Microplastics*, The Handbook of Environmental Chemistry, vol. 58, M. Wagner, S. Lambert, Eds. (Springer, 2018), pp. 203–221.
149. B. R. Baechler, H. De Frond, L. Dropkin, G. H. Leonard, L. Proano, N. J. Mallos, Public awareness and perceptions of ocean plastic pollution and support for solutions in the United States. *Front. Mar. Sci.* **10**, 1323477 (2024). doi:10.3389/fmars.2023.1323477
150. L. S. Dilkes-Hoffman, S. Pratt, B. Laycock, P. Ashworth, P. A. Lant, Public attitudes towards plastics. *Resour. Conserv. Recycling* **147**, 227–235 (2019). doi:10.1016/j.resconrec.2019.05.005
151. S. M. C. Davison, M. P. White, S. Pahl, T. Taylor, K. Fielding, B. R. Roberts, T. Economou, O. McMeel, P. Kellett, L. E. Fleming, Public concern about, and desire for research into, the human health effects of marine plastic pollution: Results from a 15-country survey across Europe and Australia. *Glob. Environ. Change* **69**, 102309 (2021). doi:10.1016/j.gloenvcha.2021.102309
152. European Commission, "Attitudes of European citizens towards the environment" (European Commission, 2020).
153. M. Felipe-Rodriguez, G. Böhm, R. Doran, What does the public think about microplastics? Insights from an empirical analysis of mental models elicited through free associations. *Front. Psychol.* **13**, 920454 (2022). doi:10.3389/fpsyg.2022.920454 Medline
154. J. Kramm, S. Steinhoff, S. Werschmöller, B. Völker, C. Völker, Explaining risk perception of microplastics: Results from a representative survey in Germany. *Glob. Environ. Change* **73**, 102485 (2022). doi:10.1016/j.gloenvcha.2022.102485
155. German Federal Institute for Risk Assessment (BfR), "BfR-Verbraucher MONITOR 08/2023" (2023).
156. S. C. Jenkins, A. J. L. Harris, M. Osman, Influence of psychological factors in food risk assessment – A review. *Trends Food Sci. Technol.* **103**, 282–292 (2020). doi:10.1016/j.tifs.2020.07.010
157. R. Janzik, S. Koch, G. Zamariola, D. Vrbos, M. P. White, S. Pahl, N. Berger, Exploring public risk perceptions of microplastics: Findings from a cross-national qualitative interview study among German and Italian citizens. *Risk Anal.* **44**, 521–535 (2024). doi:10.1111/risa.14184 Medline
158. K. Holmberg, S. Persson, Keep plastics on a tight leash: Swedish public opinion on plastic policies. *Environ. Sci. Policy* **141**, 109–116 (2023). doi:10.1016/j.envsci.2023.01.005
159. M. Grünzner, S. Pahl, M. P. White, R. C. Thompson, Exploring expert perceptions about microplastics: From sources to potential solutions. *Microplast. Nanoplast.* **3**, 7 (2023). doi:10.1186/s43591-023-00055-5
160. United Nations Environment Programme (UNEP), "Report on the stocktake of existing activities and action towards the long-term elimination of discharges into the oceans to reduce marine plastic litter and microplastics" (UNEP, 2020).
161. S. Eckert, O. Karassin, Y. Steinebach, A policy portfolio approach to plastics throughout their life cycle: Supranational and national regulation in the European Union. *Environ. Policy Gov.* **34**, 427–441 (2024). doi:10.1002/eet.2092
162. I. M. Steensgaard, K. Syberg, S. Rist, N. B. Hartmann, A. Boldrin, S. F. Hansen, From macro- to microplastics – Analysis of EU regulation along the life cycle of plastic bags. *Environ. Pollut.* **224**, 289–299 (2017). doi:10.1016/j.envpol.2017.02.007 Medline
163. S. Nitsch, Microplastics Litigation: eine rechtsvergleichende Orientierung [Microplastics Litigation: a comparative law analysis]. *Zeitschrift für Europäisches Privatrecht (ZEuP)* (2024).
164. S. J. Morath, A. Thompson, S. Hamilton, Plastic pollution litigation. *Nat. Resour. Environ.* **36**, 41–44 (2021).
165. A. L. Allison, H. M. Baird, F. Lorencatto, T. L. Webb, S. Michie, Reducing plastic waste: A meta-analysis of influences on behaviour and interventions. *J. Clean. Prod.* **380**, 134860 (2022). doi:10.1016/j.jclepro.2022.134860
166. K. Borg, A. Lennox, S. Kaufman, F. Tull, R. Prime, L. Rogers, E. Dunstan, Curbing plastic consumption: A review of single-use plastic behaviour change interventions. *J. Clean. Prod.* **344**, 131077 (2022). doi:10.1016/j.jclepro.2022.131077
167. Z. Diana, T. Vegh, R. Karasik, J. Bering, J. D. Llano Caldas, A. Pickle, D. Rittschof, W. Lau, J. Virdin, The evolving global plastics policy landscape: An inventory and effectiveness review. *Environ. Sci. Policy* **134**, 34–45 (2022). doi:10.1016/j.envsci.2022.03.028
168. S. Nuojua, D. Cracknell, A. Heske, S. Pahl, K. J. Wyles, R. C. Thompson, Global scoping review on behavioural interventions to plastic pollution with recommendations for key sectors. *Conserv. Sci. Pract.* **6**, e13174 (2024). doi:10.1111/csp2.13174
169. C. Völker, J. Kramm, M. Wagner, On the creation of risk: Framing of microplastics risks in science and media. *Glob. Chall.* **4**, 1900010 (2020). doi:10.1002/gch2.201900010
170. T. Wardman, A. A. Koelmans, J. Whyte, S. Pahl, Communicating the absence of evidence for microplastics risk: Balancing sensation and reflection. *Environ. Int.* **150**, 106116 (2021). doi:10.1016/j.envint.2020.106116 Medline
171. K. A. Willis, I. Van Putten, B. D. Hardesty, Addressing cultural context is the missing piece in policy solutions to plastic pollution. *Environ. Sci. Policy* **159**, 103829 (2024). doi:10.1016/j.envsci.2024.103829

172. California State Water Board, SB-1422 California Safe Drinking Water Act: microplastics (2018).
173. I. E. Napper, A. Bakir, S. J. Rowland, R. C. Thompson, Characterisation, quantity and sorptive properties of microplastics extracted from cosmetics. *Mar. Pollut. Bull.* **99**, 178–185 (2015). doi:10.1016/j.marpolbul.2015.07.029 Medline
174. Nordic Council of Ministers, "Global criteria to address problematic, unnecessary and avoidable plastic products" (2024); https://www.norden.org/en/publication/global-criteria-address-problematic-unnecessary-and-avoidable-plastic-products.
175. European Commission, "Amending Annex XVII to Regulation (EC) No 1907/2006 of the European Parliament and of the Council concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) as regards synthetic polymer microparticles" (2023).
176. European Union, "Directive (EU) 2019/904 on the reduction of the impact of certain plastic products on the environment" (2019).
177. Food and Agriculture Organization (FAO), "Towards the development of a Voluntary Code of Conduct on the sustainable use of plastics in agriculture" (2023); https://www.fao.org/fsnforum/call-submissions/voluntary-code-conduct-sustainable-use-plastics-agriculture.
178. J. van Dijk, R. Figuière, S. C. Dekker, A. P. van Wezel, I. T. Cousins, Managing PMT/vPvM substances in consumer products through the concepts of essential-use and functional substitution: A case-study for cosmetics. *Environ. Sci. Process. Impacts* **25**, 1067–1081 (2023). doi:10.1039/D3EM00025G Medline
179. M. Bergmann, H. P. H. Arp, B. Carney Almroth, W. Cowger, M. Eriksen, T. Dey, S. Gündoğdu, R. R. Helm, A. Krieger, K. Syberg, M. B. Tekman, R. C. Thompson, P. Villarrubia-Gómez, A. K. Warrier, T. Farrelly, Moving from symptom management to upstream plastics prevention: The fallacy of plastic cleanup technology. *OneEarth* **6**, 1439–1442 (2023). doi:10.1016/j.oneear.2023.10.022
180. F. N. F. Parker-Jurd, N. S. Smith, L. Gibson, S. Nuojua, R. C. Thompson, Evaluating the performance of the 'Seabin' – A fixed point mechanical litter removal device for sheltered waters. *Mar. Pollut. Bull.* **184**, 114199 (2022). doi:10.1016/j.marpolbul.2022.114199 Medline
181. R. C. Thompson, S. Pahl, E. Sembiring, Plastics treaty – research must inform action. *Nature* **608**, 472 (2022). doi:10.1038/d41586-022-02201-0 Medline
182. M. Wagner, M. Monclús, H. P. H. Arp, K. J. Groh, M. E. Løseth, J. Muncke, Z. Wang, R. Wolf, L. Zimmermann, State of the science on plastic chemicals - Identifying and addressing chemicals and polymers of concern. Zenodo (2024); https://doi.org/10.5281/zenodo.10701706.
183. P. Landrigan, C. Symeonides, H. Raps, S. Dunlop, The global plastics treaty: Why is it needed? *Lancet* **402**, 2274–2276 (2023). doi:10.1016/S0140-6736(23)02198-0
184. K. Raubenheimer, N. Urho, "Science-policy interface for plastic pollution" (GRID-Arendal, 2022).
185. OECD, "Global plastics outlook: Policy scenarios to 2060" (OECD Publishing, 2022).
186. M. W. Ryberg, M. Z. Hauschild, F. Wang, S. Averous-Monnery, A. Laurent, Global environmental losses of plastics across their value chains. *Resour. Conserv. Recycling* **151**, 104459 (2019). doi:10.1016/j.resconrec.2019.104459

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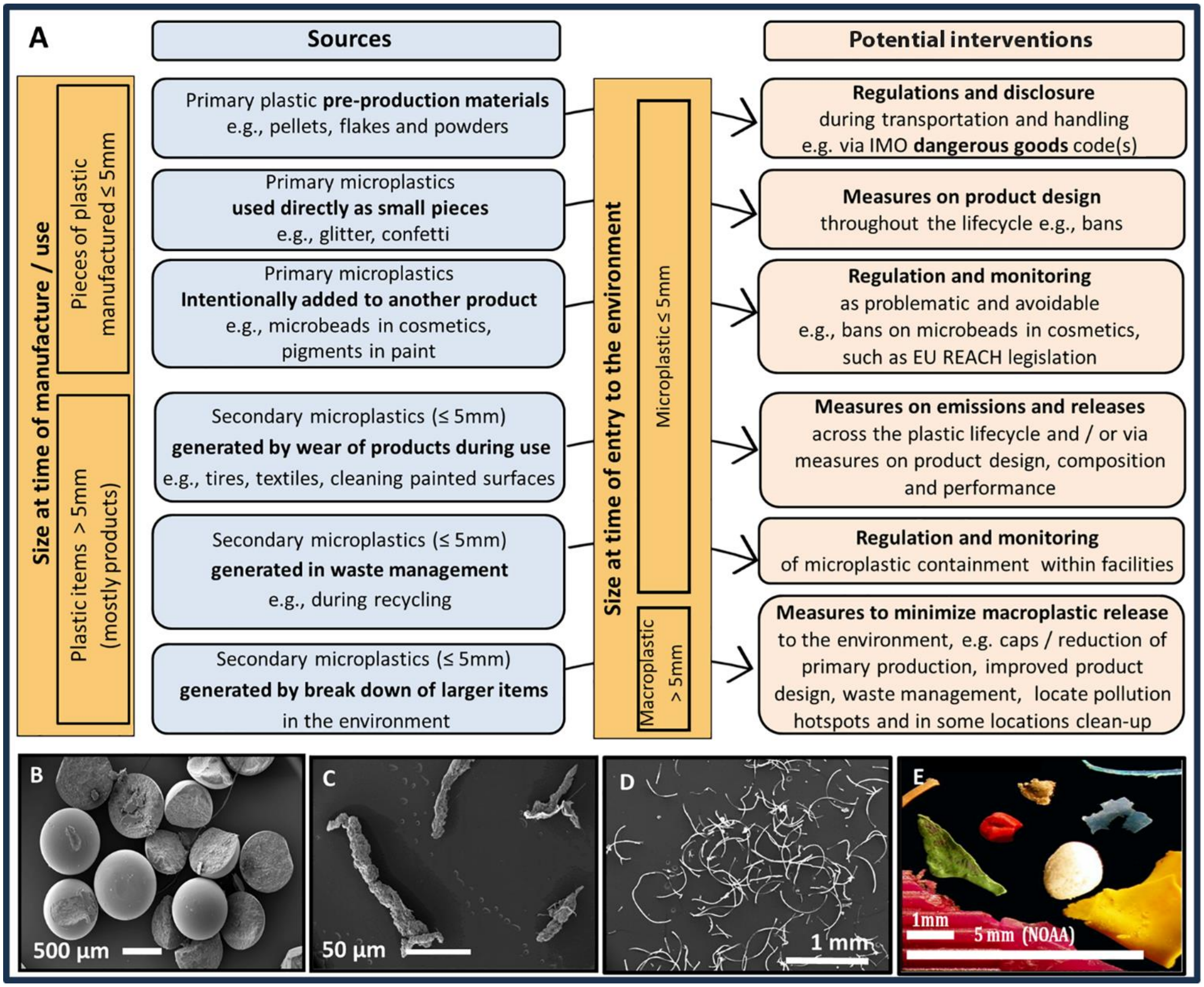

Fig. 1. Categories and sources of microplastic. (A) Scheme outlining our proposed nomenclature for microplastic categorization based on origin and size; together with potential interventions. (B to E) Images of various categories of microplastics: microbeads from cosmetics, an example of primary microplastics (B); particles from vehicle 6 tires (C); and fibers released from textiles (D), both of which are secondary microplastics generated by wear, and microplastics generated by fragmentation in the environment (E). Scale bars in (E) relate to the SI definition of micro (<1mm) and the size definition for microplastics adopted by policymakers in the US and EU (≤5mm). Images courtesy of Plymouth Electron Microscopy Centre (B) to (D) and M. A. Browne (E).

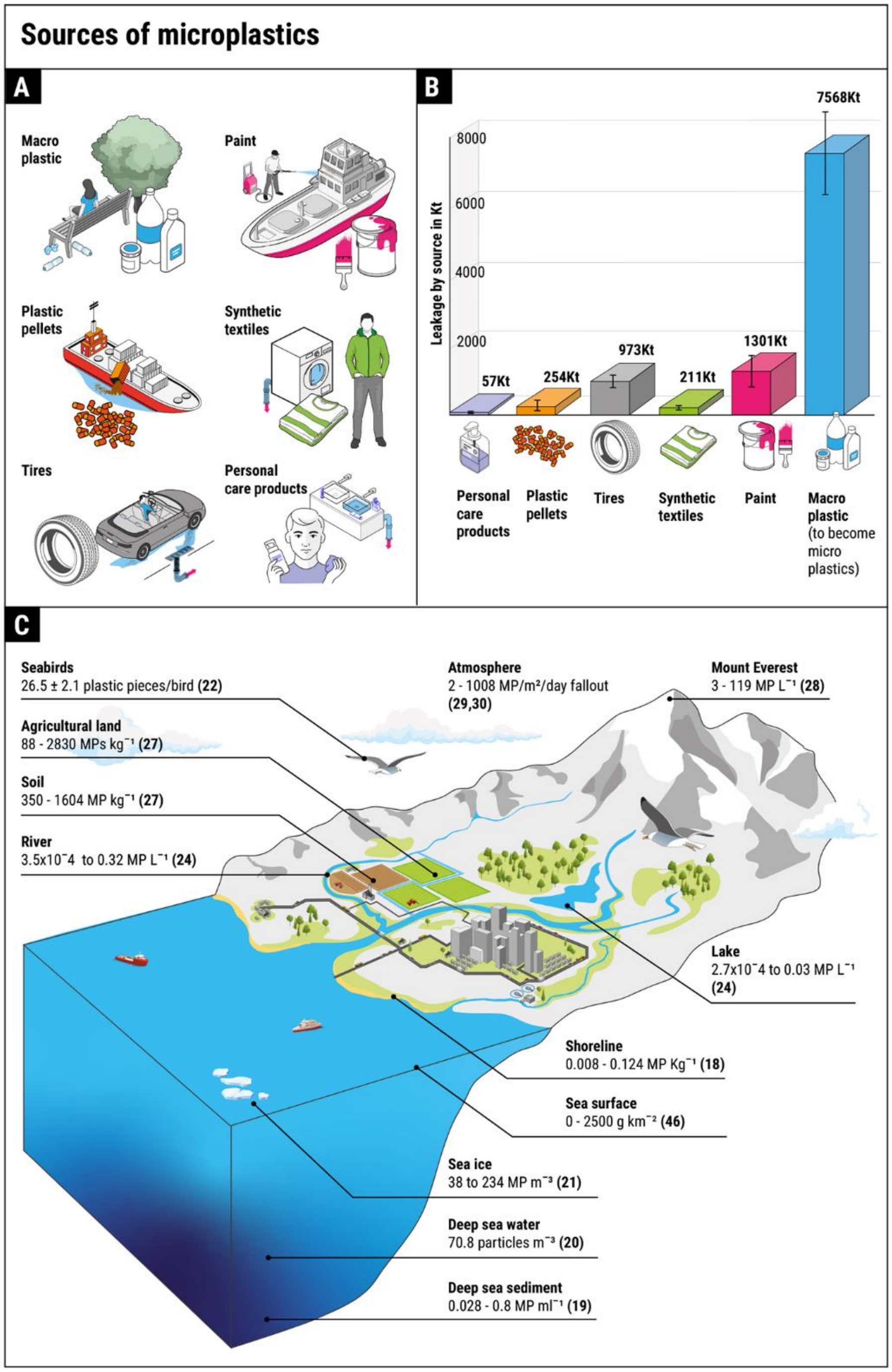

Fig. 2. Sources and pathways leading to environmental accumulation of microplastics. (**A**) Human activities leading to six key sources of microplastics; (**B**) the relative contribution of each to the marine environment (for source data see Table 1), together with (**C**) quantities reported in various environmental compartments. Note that inter-comparisons between environmental compartments should be made with caution because of variations in methods of sampling and enumeration.

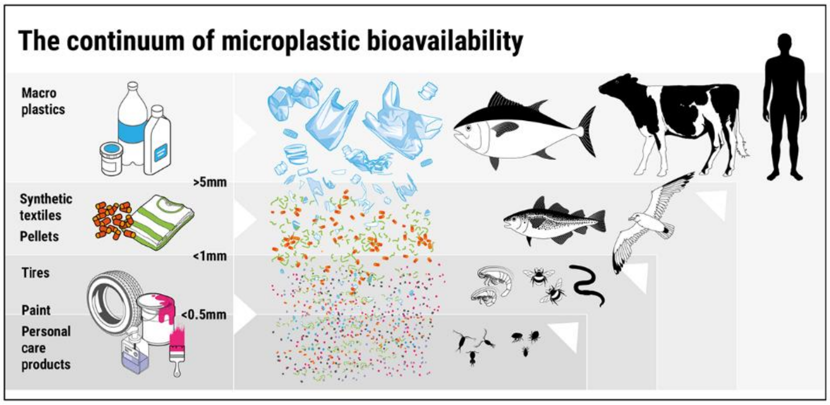

Fig. 3. Bioavailability of plastic and microplastic, according to size and key sources. As plastic items fragment into ever smaller pieces they become available to a wider range of organisms (descending horizontal rows) and the potential for transfer along food chains also increases (diagonal arrows).

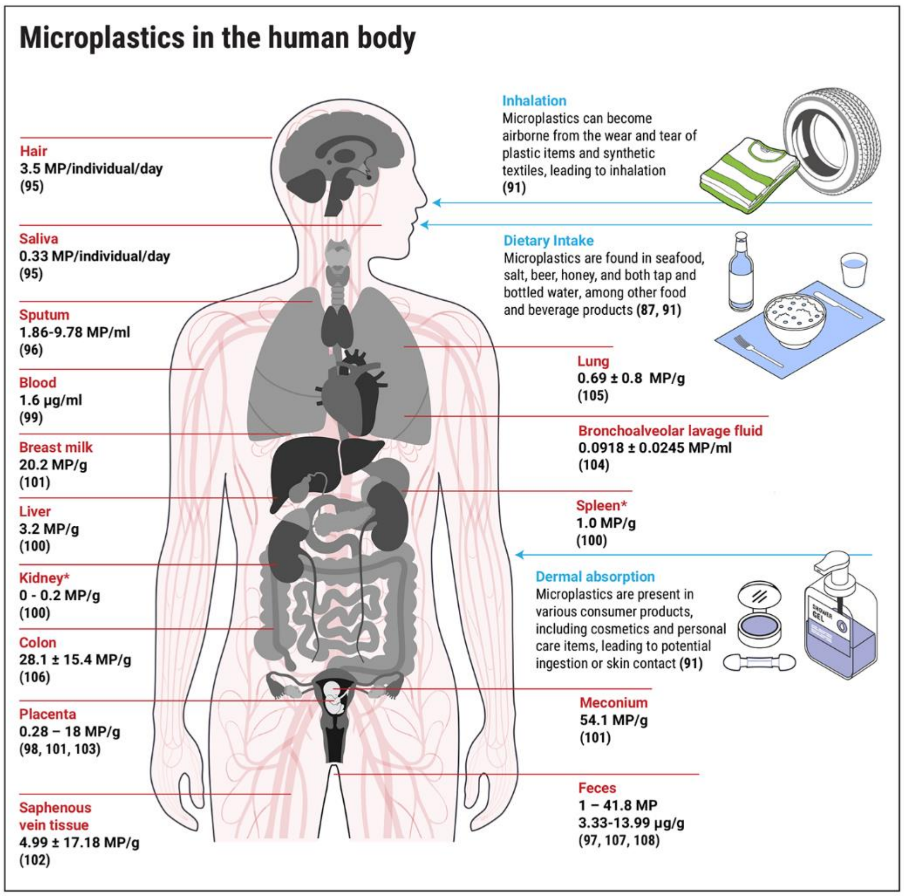

Fig. 4. Locations in the human body where microplastics have been reported. Exposure pathways (turquoise labels) and reported quantities (red labels) are shown. Quantities are as reported in each study and have not been further QA/QC screened for this review. Inter-comparisons should be made with caution due to variation in methods and units of reporting between studies. Since some methods do not characterise individual particles it is likely that quantities reported by mass relate to both micro and/or nano particles (see section Methodological advances for discussion). *Quantities reported as being around the limit of detection.

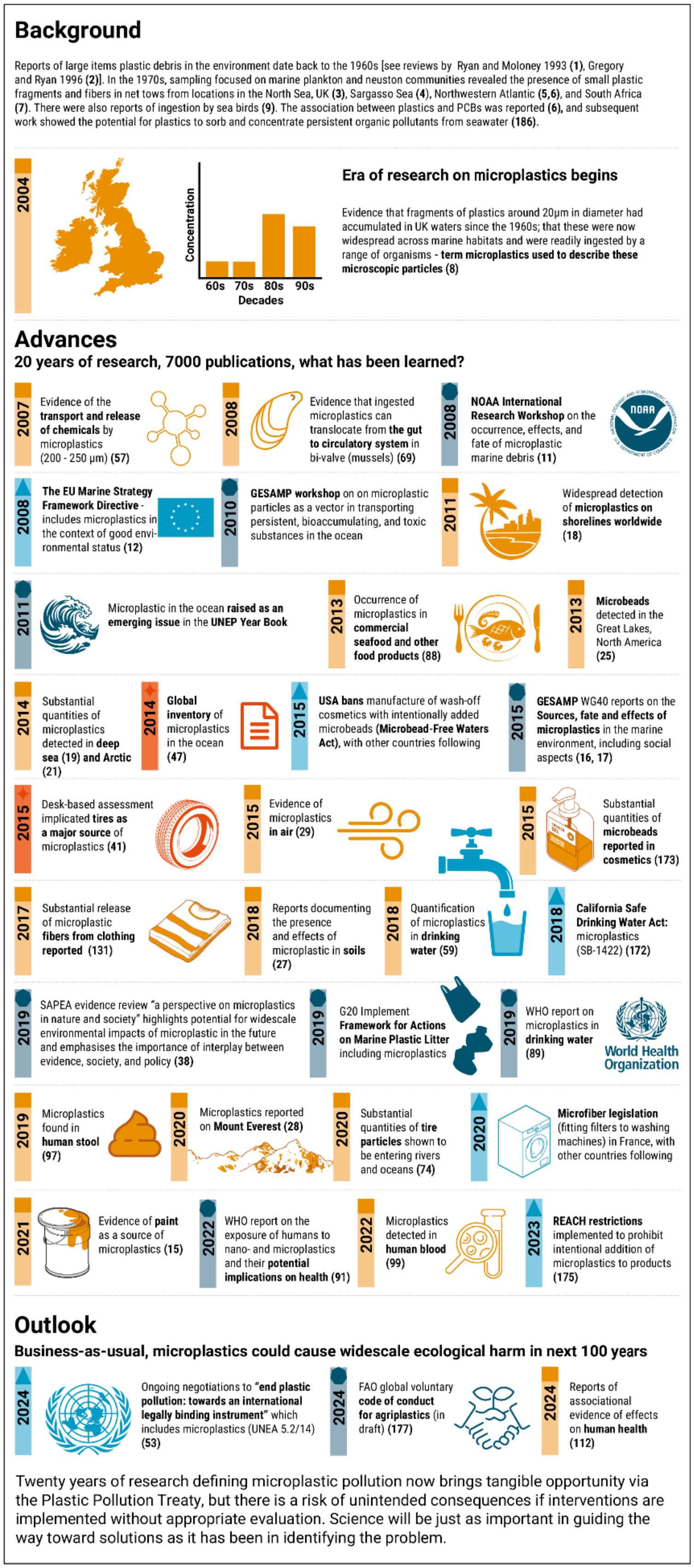

Fig. 5. The era of microplastics research. Timeline illustrating the key background together with examples of key empirical research (light brown), reviews (orange), policy focused expert reports (light blue) and legislation (dark blue) that followed directly or indirectly after the 2004 paper *Lost at sea: where is all the plastic?*

Table 1. Estimated quantities of microplastics entering the marine environment annually. The major sources and their relative contribution in kilotonnes (Kt). 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 parenthesis, averages and standard deviations are used in Fig. 2B.

Source in Kt	Boucher and Friot (2017) (*13*)	UNEP (2018) (*34*)	PEW and Systemiq (2020) (*14*)	Paruta *et al.* (2021) (*15*)	Jambeck *et al.* (2015) (*43*)	OECD (2022) (*185*)	Ryberg *et al.* (2019) (*186*)	Earth Action (2023) (*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	11000		4800- 12700 [8000]	6000			7568	2562.85