Plastics and Microplastics

A THREAT TO THE ENVIRONMENT AND HEALTH

ENVIRONMENT & HUMAN HEALTH, INC.

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Research and publication of this report
was made possible by a grant from the
Forrest & Frances Lattner Foundation.

ENVIRONMENT & HUMAN HEALTH, INC.
1191 Ridge Road • North Haven, CT 06473
Phone: (203) 248-6582 • info@ehhi.org
www.ehhi.org

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Gaboury Benoit, Ph.D.
Yale University

This project was developed and managed by Environment and Human Health, Inc.

Nancy Alderman, MES
PRESIDENT
Environment and Human Health, Inc.

EDITING AND GRAPHIC DESIGN
Jane M. Bradley, MALS
Medical/Science Writer
Environment and Human Health, Inc.

Printed on recycled paper with soy-based inks`

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1. Introduction

Plastics in the environment cause multiple problems, including entanglement, suffocation, and direct ingestion, leading to clogging animals' stomach and intestines.

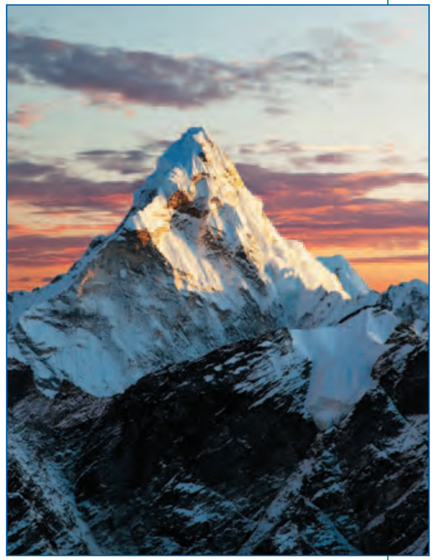
- Environmental pollution by synthetic polymers, commonly called plastics, has been an important and growing problem for decades.
- Plastics in the environment cause multiple problems for animals, including entanglement, suffocation, and direct ingestion, leading to clogging of their stomachs and intestines.
- Huge, permanent garbage patches are found in circular currents — called marine gyres — in the centers of oceans as well as on many beaches worldwide. This marine debris comes from abandoned fishing gear, direct discharges at sea, and, mainly, sources on land.
- Each year, more than 380 million metric tons (MT) of plastic are produced, similar to the weight of all the people on earth, and the amount is increasing. Of this total, only 60% is known to be disposed of in landfills or recycled, and the rest is thought to wind up in the environment.

1 metric ton (MT) = 2,200 pounds

anthropogenic litter = solid waste pollution caused by human activity

5 millimeters (mm) = 0.2 inches

- While this problem is well-known and widely discussed for the ocean, it is also a major crisis on land. Plastic adds 20% to the amount of waste in landfills and comprises the vast majority of anthropogenic litter found on our streets.
- On land as in the ocean, plastics cause the same physical problems for fresh water animals, entangling and suffocating them. Plastic litter also clogs catch basins and small streams, causing flooding. Plus, unsightly litter can lead to perception of a degraded environment, which leads to further environmental abuse and neglect.
- Pure plastics are relatively inert or unreactive, but they include numerous toxic substances added to modify their physical qualities or to make them fire resistant. They also can unintentionally adsorb, and serve as carriers for, an almost endless variety of chemicals, many of which are harmful to plants, wildlife, and humans.
- But just as bad, macroscopic plastic litter is the main source of microplastics (MPs), tiny bits 5 mm and smaller that are being increasingly linked to numerous environmental harms and possibly even human health impacts.
- Over the past decade, scientists have found microplastics in every environment they have tested, from the deepest ocean trenches to the tops of the highest remote mountains, and from the tropics to the poles.
- Microplastics are in the air and on surfaces around you right now, and they are present in your digestive tract and lungs. Microplastics are ubiquitous in our air, water, soils, and food.
- It is likely that the vast majority of macroplastics wind up as microplastics, which because of their small size and physical properties, tend not to concentrate in large, visible "garbage patches"



Over the past decade, scientists have found microplastics in every environment they have tested, from the deepest ocean trenches to the tops of the highest remote mountains, and from the tropics to the poles.

but instead are broadcast globally. Nowhere on earth is free of them; there is no litter on the summit of Everest, but there are microplastics.

Microplastics are in foods ranging from fruits and vegetables, to beer, to salt, to honey, to water — both bottled and from the tap.

- And microplastics are more than just smaller macroplastics. Their small size means that they can travel globally on the wind, and move through food chains on land and water.

- They can be filtered from water and ingested by small animals, and pass to larger animals including seafood eaten by people. Microplastics are in foods ranging from fruits and vegetables, to beer, to salt, to honey, to water — both bottled and from the tap.

- As macroplastics break down to microplastics, their surface area increases exponentially, as does their capacity to adsorb and carry toxic chemicals, pathogenic microorganisms, and antibiotic-resistant genes.

- There has been an explosion in the amount of research being conducted on microplastics, a reflection of the scientific community's concern about this potential problem.

- There is probably no other contaminant that is as abundant and widely distributed in the environment as microplastics, and we remain uncertain about their negative consequences.

- Serious harmful outcomes have been documented in the laboratory for a wide variety of organisms, but usually using elevated levels of microplastics (higher than in nature) to be able to observe effects rapidly.

- Harms range broadly from irritation and inflammation of the digestive tract to colonization by microorganisms. These elevated level studies are standard in science, but should be followed by much longer-term experiments using more realistic microplastic levels.

- Finally, looming on the horizon is a potentially larger and more serious problem: nanoplastics. This is the name given to the tiniest plastic fragments (< 0.1 µm or 0.0001 mm), which are small enough to pass through our best filters and even to cross cell walls and enter the bloodstream — and all the organs in the body.

- Our understanding of this contaminant category remains in its infancy, but demands immediate attention. Both microplastics and nanoplastics come mainly from macroplastics, and there is no realistic way to remove the small particles from the environment.

- Instead we need to reduce their source, working at every level from individual to global, enlisting government, industry, and researchers, and using tools ranging from plastic substitutes, to real recycling, to extended producer responsibility.

- Given time, nature has incredible self-cleansing capabilities, but first the source of harm must be eliminated. Recommendations for doing so comprise the final section of this report.

Finally, looming on the horizon is a potentially larger and more serious problem: nanoplastics. This is the name given to the tiniest plastic fragments.

1 µm = 1 micrometer = 1 millionth of a meter

Nanoplastics
0.1 µm (0.0001 mm) = one ten-thousandth of a millimeter (a tiny fraction of an inch)

2. The History of Plastics

Phonograph records were produced from shellac from the 1890s until the 1950s, eventually replaced by more flexible and cheaper synthetic vinyl.

- Several natural biological compounds have chemical properties similar or identical to plastics. These biological substances can be waterproof, chemically resistant, and electrically non-conductive. They include natural rubber, gutta percha, and shellac.

- The latter is secreted by the lac bug, then ground and dissolved in alcohol to be molded before drying. Phonograph records were produced from shellac from the 1890s until the 1950s, eventually replaced by more flexible and cheaper synthetic vinyl. Use of natural rubber is believed to go back at least 3000 years to the Mesoamerican Olmec culture.

- The range of substances known as plastics were first synthesized at many different times over the past 150 years and began to be used commercially thereafter. Among the earliest were polystyrene (1839), celluloid (first called Parkesine after its inventor in 1855), polyvinyl chloride (or PVC, in 1872), rayon (1892), polyethylene (1898), Bakelite (1907, also named for its inventor), polystyrene (1933), and nylon (1935).

- Almost all plastics initially had very specialized uses like phonograph records (shellac), buttons (casein), or combs (cellulose nitrate), and were not produced in large quantities. A few early uses of plastics in relatively large amounts include phenolic resins employed as electrical insulation beginning in the 1920s, and celluloid, which was used for film stock.

- An early scientific breakthrough was work conducted in the 1920s by Hermann Staudinger revealing that plastics are composed of long chain molecules, a discovery for which he was awarded the 1953 Nobel Prize.

- Between the wars, consumer products began to appear, made from various plastics. In 1930, the 3M Company introduced Scotch tape, first for masking, but then as a transparent product with multiple uses. Plexiglas, also sold as Perspex, found application as a safe alternative to conventional glass, and one that could be formed in convoluted shapes, as in the cowling for aircraft, beginning in the 1930s.

- Nylon was patented by DuPont in 1935, leading to replacement of stockings made from viscose (a different plastic, rayon) that had been popular starting in the 1910s.

- The first toothbrush with nylon tufts is believed to have been sold in 1938, the same year that DuPont chemist Roy Plunkett accidentally discovered PTFE (trademark Teflon). But it wasn't until the 1950s that the wife of an engineer convinced her husband to apply PTFE to her cookware, and nonstick cooking was started.

- Dr. Harry Coover, of Eastman Kodak, invented Super Glue (methyl cyanoacrylate) in 1942. Dow Chemical also released plastic wrap (under the trademark Saran, which is based on the discoverer's wife's and daughter's names: Sarah and Ann), in 1949. It has been very useful in reducing food spoilage and waste.

The first toothbrush with nylon tufts is believed to have been sold in 1938, the same year that DuPont chemist Roy Plunkett accidentally discovered PTFE (trademark Teflon).

In 1969, when Neil Armstrong planted a U.S. flag on the moon, it was made from nylon.

- In the 1940s, Earl Tupper developed plastic containers with self-sealing lids and marketed them via an innovative system where housewives sold to each other for a commission. These Tupperware parties became a model for sales of a number of other products, and provided a source of income for women displaced from jobs they had occupied during the war. Shortly thereafter, polyethylene began to be used to produce millions of plastic containers that rapidly displaced glass for sales of shampoo, liquid soap, and many other products.

- Dow chemical introduced expanded polystyrene in 1954. Its extremely low density (about 5% that of water) and excellent insulation ability, made it useful for a number of products. The name Styrofoam technically applies only to Dow's blue building insulation, but the word is used generically to refer to various cups, food containers, and many other products.

- The polyethylene bag made its first appearance in the 1950s, but became widely popular in the 1960s. The modern, lightweight, shopping bag is often credited to engineer Sten Gustaf Thulin. In the early 1960s, he developed a method to fabricate bags cheaply from a flat tube of plastic. It is estimated that today one trillion plastic bags are used and discarded each year.

- Although they were marketed as early as 1948, disposable diapers took off with the introduction of Proctor and Gamble's Pampers in 1961. Today it is estimated that they constitute about 2% of all municipal waste.

- Through the final decades of the 20th century, plastic products became increasingly common, often displacing natural alternatives. These ranged from Formica (1947), Velcro (1955), Lycra (1949), polyester no-iron fabrics (1953), Hula Hoops (1957), Barbie Dolls (1959), Legos (1958), Kevlar (1965), polyethylene terephthalate

(PET) beverage bottles (1973), Swatches (made from mainly plastic components, 1983), to biodegradable plastic (1990).

- In 1969, when Neil Armstrong planted a U.S. flag on the moon, it was made from nylon.

- The most recent, and probably most misunderstood chapter in the history of plastics relates to recycling. All used plastic can be converted into new products, but gathering it, sorting it, chipping it, and melting it down is rarely economically feasible. Plastic also degrades each time it is reused, meaning it can only be recycled once or twice under the best circumstances.

- In 1970, the Container Corporation of America (CCA), a leading manufacturer of corrugated paperboard and boxes, held a contest to design a new label for recycling efforts and to raise awareness about recycling.

- Gary Anderson, a 23-year-old student at the University of Southern California won the competition with a triangular symbol, based on the Möbius strip, a design which sought to capture the notion of materials returning to their point of origin and being recycled. Subsequently, the symbol has sometimes included the words "reduce," "reuse," and "recycle" to spell out the goals that were being symbolized.

- The symbol eventually fell into the public domain. But in 1988, the Society of the Plastics Institute (SPI) developed their own system of codes to facilitate the sorting of plastics.

- The SPI, today known as the Plastics Industry Association, originated the Resin Identification Codes (RIC), a symbol comprised of three arrows forming a triangle with a number in the center. The numbers, from one to seven, refer to the resin from which the

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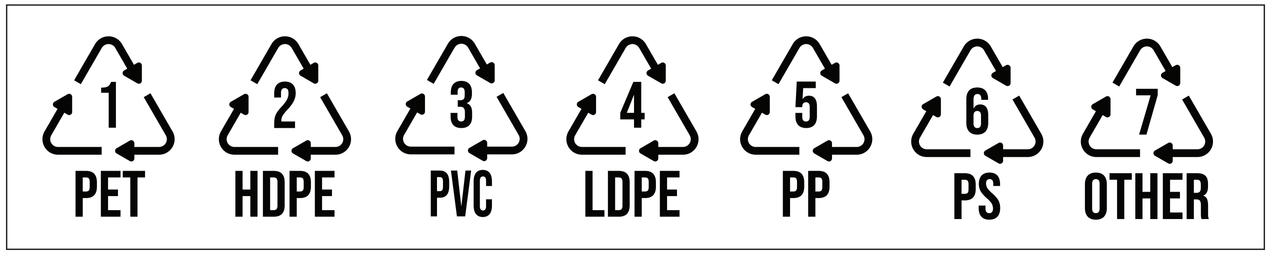

container is made, with the last, number seven, meaning "other," which can be dozens of different plastic compounds.

- Ostensibly, the coding was supposed to facilitate recycling by allowing sorting (different plastics cannot generally be combined), but it came to be confused with an indication that the plastic so marked was recycled or recyclable.

- Almost all recycled plastic is in fact types 1 and 2, and even with these, only 10% of all plastic is ever recycled. Furthermore in 2018, China — which had been buying 70% of the world's waste plastic — effectively stopped, causing plastics recycling worldwide to grind to a halt.

- Many argue that the RIC is just a clever way for the plastics industry to sow confusion and give the impression that recycling is solving the plastics problem. The plastics industry mounts a $50 million-a-year ad campaign promoting the benefits of plastic, and has lobbied 40 states to mandate that the symbol appear on all plastic whether it can be recycled or not.

- Considering that the oil industry earns $400 billion a year manufacturing plastic from raw materials, the industry may consider losing 10% of their profits to recycling a small price to pay. Furthermore, many well-meaning individuals have developed a false sense that they are protecting the environment by recycling, when in fact using plastic in the first place adds to the waste epidemic and all the problems that plastics are causing in our environment.

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3. The History of Plastic Pollution

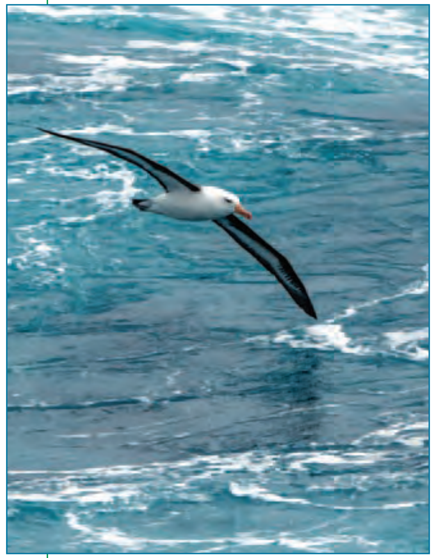
- Plastics are light, durable, inexpensive, versatile, and *relatively* inert (unreactive). It is no wonder that they have become an extremely popular material for a wide variety of uses.

- Plastics of various kinds have existed for almost 200 years, and natural rubber has been used for over 3000 years, but their use has exploded over the past 70 years.

- In 1950, there was less than 1 million metric tons (MT = 1000 kg) of plastic produced annually, but the amount exceeded 300 million MT by 2015, and is increasing. By comparison, the total weight of people on earth is about 500 million MT, so the amount of plastic produced per person annually may soon exceed our bodyweight.

- Roughly half of this plastic is for single use products, like packaging, and about 40% of plastic waste is not disposed of in managed landfills or recycled.[1] Rates of responsible management vary a great deal globally, with levels in the U.S. being relatively high.

It is important to realize that recycling has been more of a public relations scheme by the plastics industry than an actual waste management strategy.
Less than 10% of all plastic produced has been recycled.



Awareness of plastics pollution started first with the oceans. Perhaps the earliest account of wildlife ingesting plastics was not until 1969, when the stomachs of a sea bird (albatross), were documented to contain plastics.

- It is important to realize that recycling has been more of a public relations scheme by the plastics industry than an actual waste management strategy. Less than 10% of all plastic produced has been recycled, and plastic items can only be remanufactured a few times before chemical degradation makes further recycling impossible.

- Plastics producers promoted the well-known triangular recycling symbol and set of seven plastics types, but this only gives an illusion of recyclability. Almost all of the small amount of plastics that is actually recycled is in categories 1 and 2 — polyethylene terephthalate (PET) and high density polyethylene (HDPE). Only a tiny fraction of categories 3 through 7 are ever recycled even once.

- Awareness of plastics pollution started first with the oceans. Perhaps the earliest account of wildlife ingesting plastics was not until 1969,[2] when the stomachs of a sea bird (albatross), were documented to contain plastics.

- By the 1970s, when production was only around 50 million MT/yr, marine plastics pollution began to be documented by scientists with greater frequency,[3] indicating that the problem was growing.

- For example, researchers conducting plankton tows to evaluate the effects of a nuclear power station on the ecology of Niantic Bay, Connecticut, were surprised to find tiny plastic particles in their nets in addition to the expected microscopic organisms.

- They went on to observe that the "spherules have bacteria on their surfaces and contain polychlorinated biphenyls (PCBs), apparently absorbed from ambient seawater, in a concentration of 5 parts per million." They documented that white, opaque spherules had been selectively consumed by eight species of fish out of 14 species they examined. This is perhaps the first observation of seafood contaminated by microplastics.

- There were a few similar early observations of plastic as a new category of pollution, but only in the 1980s did the expression "marine debris" replace the ancient categories of flotsam and jetsam.[4]

- Beach clean ups, which turned up substantial amounts of plastics, drew popular attention to the problem beginning in the 1980s, though at first it was controversial whether the litter had been dropped in place or floated in on the tides; it was the latter.

- Discovery of the Great Pacific Garbage Patch (GPGP) in 1997 further spurred public awareness of this problem. The GPGP is a vast area of floating plastics trapped in circular currents between California and Hawaii and now observed in similar areas elsewhere.

- In recent decades, an exponential growth in the production of plastics, and of its release into the environment has led to an explosion of interest in this topic. Recently, of the 275 million MT of plastic produced in the year 2015, 5–13 million MT were estimated to have been discharged to the ocean as macroscopic litter and microplastics.[5]

- Without improvements in waste management infrastructure, the amount of plastic waste likely to enter the ocean from land by 2025 is predicted to increase to 10 times that amount. Even though nearly 80% of marine plastics comes from land, being discharged to the sea from rivers, awareness of terrestrial plastics pollution has come much later than for the ocean.

- Scientific research on plastics in rivers has become common only in the past decade.[6] The same could be said for awareness and understanding of microplastics pollution, a problem virtually unknown before 2010, but which has since become an enormous concern.

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- One recent analysis showed the number of studies on microplastics almost doubling each year over the last decade, with the number increasing from 20 to 2000 in that time.[7] This increase is one clear indication of the uneasiness of scientists about this poorly understood, but potentially very serious, problem.

- Plastics are thought to be such a permanent and significant addition to the environment that geologists and ecologists have proposed that a plastic-rich layer may eventually serve as a sedimentary marker of the Anthropocene, the geologic era dominated by humanity.[8] Others have suggested that "Plasticene" might be a better new name for the current era,[9, 10] an idea first proposed by Curt Stager in the 2011 book, *Deep Future.*

- There is very little research that documents possible changes in impacts on organisms as plastic in the environment has increased, but most point to a growing problem. For macroplastics between 1997 and 2015, the number of species known to have been affected

by either entanglement or ingestion of plastic debris has doubled, from 267 to 557 species among all groups of wildlife.[11]

- One study used museum specimens of fish to evaluate microplastics going back as far as 1900. As might be expected, no MPs were found in fish before 1950, but concentrations showed a significant increase from 1950 until 2018, the last year studied.

- The authors concluded that plastic pollution in common freshwater fish species is increasing and prevalent across individuals and species, and is likely related to changes in environmental concentrations.[12]

- Other researchers evaluated marine litter regurgitated by marine birds (albatrosses and giant petrels) between 1996 and 2018.[13] They found that non-fishing litter increased across all species over those two decades.

- A single study found no change for the Baltic in plankton samples and in digestive tracts of two economically and ecologically important planktivorous forage fish species over the past three decades.[14] This contrasting result may reflect local conditions or differences in methodologies.

- Data are lacking that could be used to draw firm conclusions about changing historical levels of macro- and microplastics in the environment. Many locations and methods have been used, and collecting consistent, long-term information has not been a priority.

- Existing measurements indicate very high variability depending on location, what fraction (especially size) was measured, and what analytical methods were used. Differences can range over orders of magnitude for similar locations.

- What is clear is that the highest amounts recorded can be very elevated. As one example, drinking water MP number concentrations

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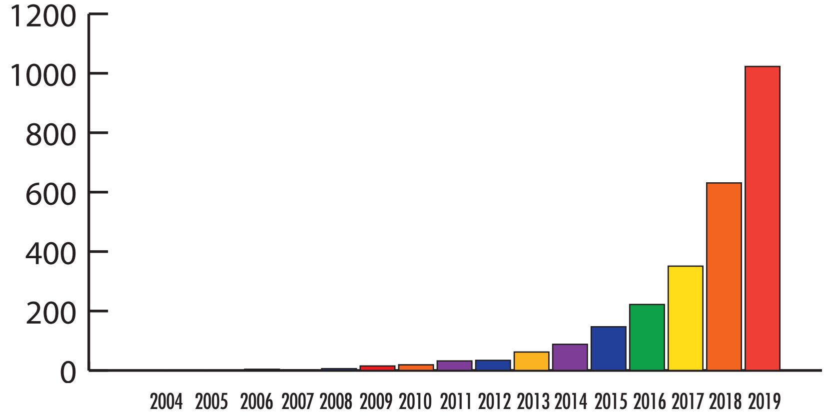
Figure 1. Number of Publications on Microplastics



Annual number of publications on microplastics (MPs) research from 2004 to 2019, retrieved from Web of Science Core Collection (WOSCC).

spanned ten orders of magnitude (from 10^{-2} to 10^{8} #/m^3) across individual samples and water types.[15]

- In Cypriot turtle nesting beaches, mean particle counts of 45,000 per m^3 were measured in the upper 2 cm of sand. Agricultural soils that had been exposed to biosolids and mulching film showed concentrations up to 13,000 items per kg and 4.5 mg per kg of dry soil.[16]

- Indoor air has been measured with fallout of typically near 10^4 MPs/m^2 in a residential setting.[17, 208]

- While there is no certainty, it is very likely that amounts of microplastics have tracked macroplastics, whose release is proportional to production. On that basis, it is probable that levels of all plastics in the environment have increased exponentially since they began to be used in significant amounts in the 1950s.

4. The Scale of the Plastic Problem

- The immensity of the plastic waste problem can be difficult to comprehend because it is so large. Barely starting before the 1950s, plastic production has grown to almost 400 million metric tons (MT) per year, and continues to expand.

- Soon we will be annually producing an amount of plastic equal to the weight of everyone on earth. Spatially, it is ubiquitous. Scientists have found plastics or microplastics everywhere they have looked, and there is probably no place on earth where this contamination is absent.

- Describing the magnitude of plastic waste can be confusing because of the wide variety of units employed. Both weights and numbers of items are reported and these are normalized to different volumes *or* masses of water, air, and soil, as well as per organism in the case of biological systems.

About 10% of total oil and gas production is used to produce plastics. Of all plastics produced, fully 60% ends up as waste in landfills or the natural environment.

About 10 million metric tons of plastic are lost to the ocean annually. Without a change in trajectory, it is estimated that there will be more plastic than fish in the ocean by 2050.

- About 10% of total oil and gas production is used to produce plastics. Of all plastics produced, fully 60% ends up as waste in landfills or the natural environment. About 10% of all the plastic (30–40 million MT) is both poorly managed and located within coastal zones, where populations are most dense.

- Of this amount, about 10 million metric tons of plastic are lost to the ocean annually. Without a change in trajectory, it is estimated that there will be more plastic than fish in the ocean by 2050.

- Less than 10% of all the plastic produced is ever recycled. Because of chemical damage that occurs with each reuse, plastics can only be recycled once or twice at most.

- For microplastics, estimates vary widely, but somewhere between 50,000 and 1,100,000 MT are believed to be directly discharged to the ocean.[18] But another study concluded that 13,000,000 MT of synthetic fibers alone were discharged to the ocean annually.[19]

This is in addition to all the MPs produced within the ocean by degradation of macroplastics, probably a much larger amount.

- Based on the total amount of plastics produced historically (8.3 billion MT) and its estimated loss to the ocean, we calculate there should be about 0.4 g of plastic for every square meter of sea surface. It is unknown how much of that plastic remains in the water, has settled to the bottom, or had been degraded in some way. If the 0.4 g of plastic were comprised of average MPs with a size of 0.05 mm (50 μm), there would be 800,000 MP particles for each square meter of the sea.

- Market mussels intended for human consumption were found to contain around 400 MP particles per kilogram (kg).[20] A survey of published studies found an enormous range of measured values for MPs in drinking waters, but numbers as high as 100,000 particles per liter were documented.

- Two-thirds of all textile items manufactured are now synthetic, mainly plastic polymers like polyester, polyamide, and acrylic.[21] These garments release enormous numbers of MP fibers, with one estimate of 700,000 MPs released per laundered fleece garment.[19]

- It is worth noting that huge and sometimes contradictory variations can exist both because of the inherent heterogeneity in nature, but also because of the inconsistent and non-standardized methods used by different investigators.

- It is probable that reported values are more often *underestimates* than the reverse because it is easy to miss microplastics, especially on the small end of the size range. Similarly, because of analytical challenges, nanoplastics have yet to be directly measured in nature, though it is certain that they exist.

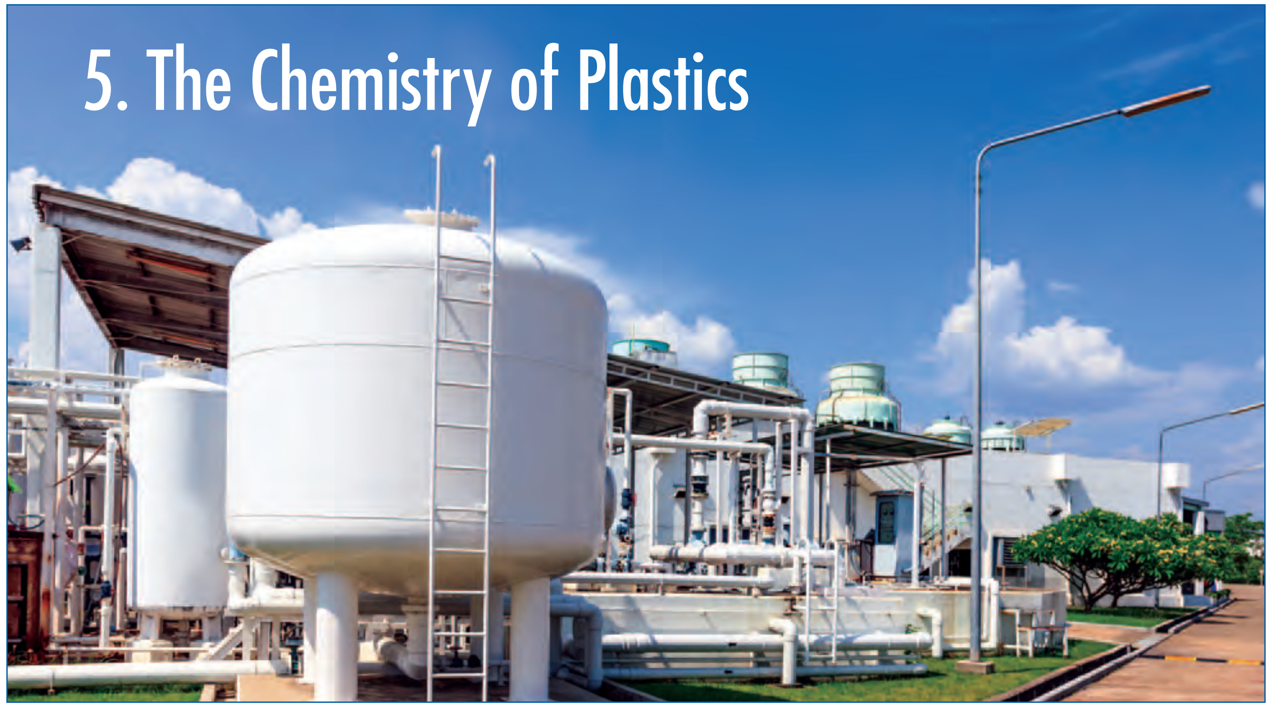
Market mussels intended for human consumption were found to contain around 400 MP particles per kilogram.

1 g = 0.035 ounce
1 ounce = 28 g
1 kg = 2.2 pounds

Nanoplastics

Because of analytical challenges, nanoplastics have yet to be directly measured in nature, though it is certain that they exist.

5. The Chemistry of Plastics



The names of many plastics begin with "poly-" followed by the name of the monomer on which it is based. The simplest formulation of plastic polymers can become more complicated, because manufacturers often include additives to give the plastics desirable chemical and physical characteristics. Furthermore, some plastics contain unintended additional chemicals as contaminants (such as metals in polyvinyl chloride (PVC).

Composition

- Plastics consist of very large molecules (macromolecules) composed of huge arrays of smaller subunits. Plastics are polymers because they are made up of smaller structural units, or monomers, linked in huge chains. As such, their chemical formula can often be expressed as that of the simple monomer followed by the subscript "n," meaning an indefinite, very large number.

- It also means that plastic polymers usually have very simple chemical formulae. As one example, polyethylene is composed entirely of carbon (C) and hydrogen (H) and can be written as $(CH_2CH_2)_n$.

- The names of many plastics begin with "poly-" followed by the name of the monomer on which it is based. The simplest formulation of plastic polymers can become more complicated, because manufacturers often include additives to give the plastics desirable chemical and physical characteristics. Furthermore, some plastics contain unintended additional chemicals as contaminants (such as metals in polyvinyl chloride (PVC).

- In addition, when macroplastics break down into microplastics, their very large surface area per mass provides locations for adsorption of many toxic persistent organic pollutants (POPs), metals, and microbes — and can transport them.

- This combination of monomers, additives, contaminants, and adsorbed substances can be released to foods and beverages that come into contact with plastics, thereby exposing humans.

- There are over a dozen common plastic types, but a few are used in greater amounts and are found more commonly in the environment as waste. Frequently encountered plastics include polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), polyvinyl chloride (PVC), polycarbonate (PC), polyester (PES), polyamide (PA), and nylon. (Abbreviations are not standard across all users.)

- In freshwater environments, PE, PP, and PS waste were found to be most common.[22] In one survey of foodstuffs, PET, PP, PE, PES, PVC, PS, PA, and nylon were observed most frequently.[23] In a review of drinking water, the descending order of frequency was PE ≈ PP > PS > PVC > PET.[15] In salt samples, the order was PE ≈ PP ≈ PET > nylon > acrylic.[24]

Additives

- The range of additives to plastics is vast. A host of chemicals are added to serve as plasticizers (increase the flexibility, durability and stretchability of polymeric films), flame retardants, antioxidants (reduce oxidative degradation), acid scavengers, light and heat stabilizers, lubricants, pigments, and antistatic agents.[25]

This combination of monomers, additives, contaminants, and adsorbed substances can be released to foods and beverages that come into contact with plastics, thereby exposing humans.

> greater than

≈ approximately equal to

Toxic chemical additives…can potentially migrate and lead to human exposures, especially if they are present in food packaging.

- Among the most commonly used chemicals to improve plastics properties are nonylphenol, phthalates (potassium acid phthalate), bisphenol A (BPA), polybrominated biphenyls (PBBs), ethers, and heavy metals.[26]

- An analysis of marine debris and equivalent new plastics identified fully 231 different chemicals.[27] The additives were of many different kinds, including hydrocarbons, ultraviolet (UV) stabilizers, antioxidants, plasticizers, lubricants, intermediates, compounds for dyes and inks, flame retardants, and others.

- Toxic chemical additives in plastic include phthalates, bisphenol A (BPA), brominated flame retardants (BFR), triclosan, bisphenone and organotins.[28]

- These additives can potentially migrate and lead to human exposures, especially if they are present in food packaging.[25]

- Perhaps the most well-known and controversial additives to plastic is BPA, which is used as plasticizer or antioxidant in PP, PE, and PVC,[27] to render PC bottles hard and clear, and to improve properties of epoxy resins used to line food cans.

- There has been an enormous amount of research on BPA in food contact with plastic materials, and health effects remain controversial. What is known is that BPA is a common additive in several plastics that contact foods, and that BPA has known health impacts on humans and animal models. What remains uncertain is whether exposure levels are high enough to cause human health impacts.

- Besides the low-level chemical additives, the monomers themselves pose some risk if they do not polymerize or otherwise leach out of the plastic. One review considered 55 resin types from the standpoint of EU and UN standards. The potentially most hazardous polymers are those built from monomers classified as mutagenic and/or carcinogenic (EU category 1A or 1B). These belong to the polymer families of polyurethanes, polyacrylonitriles, polyvinyl chloride, epoxy resins, and styrenic copolymers.

- A considerable number of polymers (31 of 55) are made of monomers that belong to the two worst of the ranking model's five hazard levels, i.e., levels IV-V.[29]

Adsorbed Materials

- Once released to the environment, plastics can break down to microplastics, which have a very large surface area for their weight. For example, medium-sized microplastics with a diameter of 0.01 mm have a surface area of at least 1 m^2 per gram (g).

- Many toxic substances, including persistent organic pollutants (POPs) and metals, are hydrophobic, and have a tendency to stick to surfaces rather than remaining in solution.

- The large surface area of microplastics can attract and harbor large amounts of these toxic hydrophobic contaminants. It also serves as a unique habitat where microbes, including hazardous pathogens, tend to grow. For example, it has been found that microplastics act as a hotspot for multidrug resistant human pathogens.[30] Thus, microplastics can serve as a carrier for multiple kinds of harmful materials that were not part of the original plastic.

- Many studies have shown that plastics contain organic contaminants, including polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), petroleum hydrocarbons, organochlorine pesticides (2,2′-bis(p-chlorophenyl)-1,1,1-trichloroethane, hexachlorinated hexanes), polybrominated diphenyl ethers (PBDEs), alkylphenols and bisphenol A (BPA), at concentrations ranging up to the mg/g level.

The large surface area of microplastics can attract and harbor large amounts of these toxic hydrophobic contaminants. It also serves as a unique habitat where microbes, including hazardous pathogens, tend to grow.

Adsorption is the process by which ions, atoms or molecules adhere to the surface of a solid material.

1 pound = 454 g
1000 mg = 1 gram

Plastics are found in sizes ranging from large molecules to enormous fishing nets that are longer than a football field.

PAH = Polycyclic aromatic hydrocarbon

1 meter (m) = about 3 ft.
1 m = 1000 mm
1 mm is slightly greater than 1/32″

- While some of these compounds are added during plastics manufacture, others adsorb from the water containing the microplastics. Studies have demonstrated that the contaminants can transfer from plastic to organisms.[31] The potential impact can be substantial.

- For example, hydrophobic organics (like phenanthrene, a PAH) preferentially adsorb to plastics (in the order of preference, PE > PP > PVC) and can then desorb later, causing exposure. It has been shown that as little as 1 µg of contaminated polyethylene added per gram of sediment can give a significant increase in phenanthrene accumulation by a common marine worm.[32]

- The wide range of contaminants, plastic resins, and potentially impacted organisms makes generalization difficult, but one review found that the negative effects of POPs adsorbed to the surface of MPs were greater than those generated by plastics additives.[26]

Physical Properties: Size Distribution

- Plastics are found in sizes ranging from large molecules to enormous fishing nets that are longer than a football field. To describe these, we usually use metric units in two ranges to cover a factor of one million variation in size.

- A meter (about 3 ft) is divided into 1000 mm (each mm is slightly greater than 1/32″). Down from there in size, we use microns (1 µm = 1/1000 mm, or 1/1,000,000 m). Small things are often compared to the diameter of human hair, which ranges from 20 µm to 180 µm (or 0.02 – 0.18 mm). The smallest size visible to the unaided eye is about 60 µm.

- Microplastics are arbitrarily considered to be pieces smaller than 5 mm (5000 µm), but larger than 0.1 µm. At the large end, MPs are easily visible to the naked eye. The lower size is close to the limit of visibility for a standard microscope. This is also the smallest-sized particle that can be captured with good water filters.

- Bacteria all fall in the same size range as MPs, though viruses are smaller still. MPs have a very large range of sizes (a factor of 5,000). It's similar to the range in size between a milk jug and a supertanker.

- A third category is nanoplastics (NPs), a topic only addressed briefly in this report. NPs are all plastic bits smaller than MPs, so they are smaller than 0.1 µm. This is the size range of viruses (at the large end) to molecules (at the lower end). Several studies indicate that the number of plastic particles increases exponentially as size decreases in both the ocean[33] and fresh water bodies.[34]

- Nanoplastics have been studied in the laboratory, but they remain poorly understood. So far, NPs have not been detected in natural aquatic systems,[35, 36] a failure of the analytical methods available, not evidence that they are not abundant.

Physical Properties: Density

- Density is an important characteristic because it determines whether plastic will float or sink, and how quickly. However, if plastic particles have gases or organic matter trapped on them or in cracks, the effective density is lower than for an unaltered equivalent. In addition, settling times tend to be long because of MP's small size.

- The table at right shows the density of various plastics and some other well-known substances, including aluminum and glass, which are also used to make recyclable containers. If the density is less than that of water, it will float, even if the container is full of water. If the density is greater than water, it will sink unless air is trapped inside, which is commonly the case.

Density Comparison Chart
(all in g/cm³)

Styrofoam	0.05
Wood (maple)	0.7
Polypropylene	0.9
Polyethylene	0.9
Fresh water	1.0
Sea water	1.02
Polystyrene	1.06
Nylon	1.08
Polyester	1.3
PET	1.4
PVC	1.45
PTFE (Teflon)	2.1
Glass	2.5
Aluminum	2.7

Measurement

- Measurement of MPs in the environment is challenging because they are so small, and difficult to distinguish from some naturally occurring materials.[37] As described earlier, most MPs are below the

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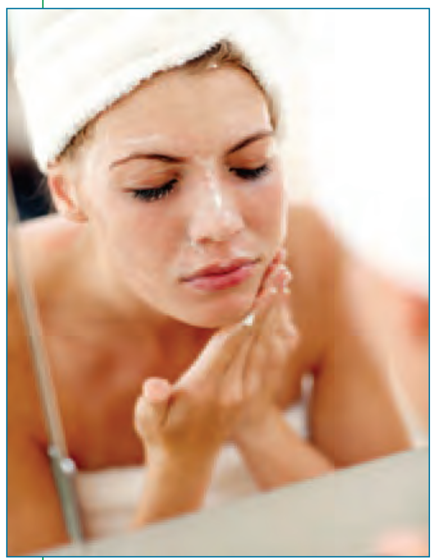
detection limit of human vision and are even challenging to see in a microscope. Several steps are required:

- *Isolation:* For air or water this usually involves filtration.
- *Identification:* This is done microscopically. Very time consuming. Not possible for the smallest MPs.
- *Separation:* Larger MPs can be hand-picked from other materials under a microscope. Rarely can MPs be definitively differentiated from other materials visually, so further characterization is required. MPs can be separated from denser geological materials (soil particles) by flotation in a dense salt solution. They can also be chemically separated, for example, with an oxidizing solution that will destroy natural organic matter.
- *Characterization:* Many chemical analytical methods can be used, though they must be able to work on very small quantities. Fourier transform infrared spectroscopy (FTIR) is probably most popular. Raman spectroscopy and GC-MS following pyrolysis are also effective. Instrumentation in all cases is expensive.

6. Microplastics and Their Sources

Two main types of microplastics are known to exist, those that are directly manufactured (microbeads) and those formed by degradation of larger pieces of plastics.

- There are two main types of microplastics that are known to exist, those that are directly manufactured (microbeads) and those formed by degradation of larger pieces of plastic.[38] The former have been used in commercial products from toothpastes to cosmetics.
- The beads are sometimes called “primary” and the fragments “secondary,” but this does not refer to their relative importance or abundance.[39, 40]
- Indeed, secondary microplastics are much more abundant than primary ones in most cases, and are thought to account for much more than 90% of MPs discharged to the ocean. We discuss the main source of secondary MPs — degradation of macroplastics — in a later section.
- From the 1990s through 2000s, cosmetic and personal care product manufacturers increasingly used plastic microbeads as a cleanser or exfoliant in facewash, shower gels, and toothpaste,[41] as well as in products like printer toner.[42]



Microbeads comprised a significant portion of the cosmetic and personal care products in which they were used, ranging from 5,000 to 50,000 beads per gram of facial scrubs, for example.

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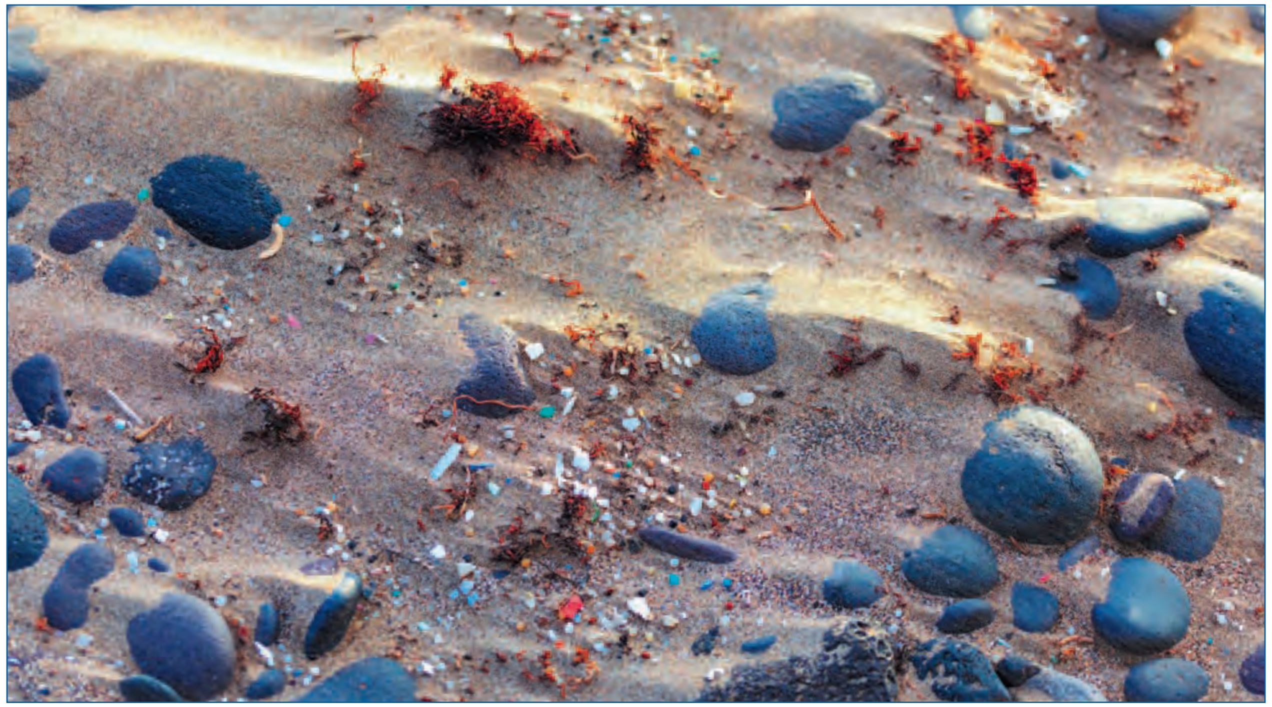
- In one study in Turkey, toothpaste was found to contain from 0.4 to 1% polyethylene in the 20% of samples tested that contained MPs.[43]
- In Malaysia, all facial scrubs tested contained MP in high quantities[44] and can range from 5,000 to 50,000 particles per gram.[45] Paint contains intentionally added microspheres ranging in size from a few to hundreds of µm.[46] Furthermore, dust from sanding of painted surfaces releases MPs in the size range from 0.05 – 3 µm.[47]
- Although potentially toxic, these particles include many constituents besides plastics.[48] A new class of intentionally manufactured "microbeads" is silver nanoparticles, which are used for their antibacterial properties.
- So far, their environmental and human health impacts are poorly known.[49, 50] Silver nanoparticles should be carefully monitored,[51] since their use is often frivolous (e.g., to reduce odor in clothing).[52]
- As a class, microbeads appear to be somewhat less effectively removed during the sewage treatment process, with only about half being transferred to sludge,[53] whereas most MPs are removed more efficiently (> 90%).[54]
- Primary microplastics are being regulated out of existence, for example, via the 2015 U.S. Microbead-Free Waters Act[55] and an EU ban on microbeads in cosmetics and personal care products that will take effect beginning in 2022.[56] Microbead use is also being reduced through consumer education.[57] They are unlikely to be a major problem in the future,[46] even if much work remains to be done.



Nurdles

Nurdles can carry pathogenic bacteria and persistent organic compounds (POPs) on their surfaces, and they have been found widely on beaches from the Gulf of Mexico to Scotland.

- Another category of manufactured microplastics is "nurdles," amorphous plastic pellets used in fabrication of other products. Sometimes called "mermaid tears" (though this expression is also used to refer to beach glass), they are typically 1 – 5 mm in size and most commonly composed of PP and PE.
- Nurdles can carry pathogenic bacteria[58] and persistent organic compounds (POPs)[59] on their surfaces, and they have been found widely on beaches from the Gulf of Mexico[60] to Scotland.[58]
- They were observed to be abundant in the gastrointestinal tracts of dead and stranded seabirds on Washington and Oregon beaches.[61] Since they are not found in consumer products, the presence of nurdles is indicative either of spills[62] or direct pollution discharges.
- There are two large sources of microplastics that are not related to plastic waste disposal or its mismanagement. These are MPs

Notably, 60% of tires are composed of additives rather than simple rubber, and these other substances are often more toxic than rubber.

originating from tires (wear particles known as TWPs) and fibers from textiles. Still, these two are very important, and clothes washing and tire abrasion (along with degradation of macroplastics) are known to be the major sources in the total emission of microplastics into the ocean.[63]

- Studies in China have shown that the highest proportion of MPs comes from tire dust and synthetic fibers, accounting for fully 54% and 29% of the total, respectively.[64] Similarly, in Sweden, about half of MPs were identified as tire wear particles.[65] TWPs are highest near roads, and constitute the dominant type of particle in air near roads.[66] Likewise, TWPs can constitute up to 15% by weight of street catch basin materials,[67] but they are found everywhere.

- Considering plastics of all sizes (including macroplastics), tire abrasion particles alone may amount to 5 – 10% of the total ending up in the ocean.[68] Unexpectedly, for the Ross Sea in distant Antarctica, fibers were the most frequent shape, and the most common material (94% by weight) was styrene-butadiene-styrene copolymer (SBS), widely used in pneumatic tires.[69] Numerous studies confirm that tire abrasion is a major source of microplastics.[68, 70-72]

- In Germany, quantities of TWPs are four times greater by mass than the amount of pesticides used in that country.[73] On a global basis it is estimated that 6.3 MT of MP come from this source[68] and it may be the dominant source of MP overall. Notably, 60% of tires are composed of additives rather than simple rubber,[74] and these other substances are often more toxic than rubber.

- Plastic fibers are released in abundance from many sources, but especially from washing synthetic garments, particularly those made from fleece. The impact of fibers on organisms is poorly understood so far, but some investigators believe that microfibers may be more harmful than other categories of MPs,[75] as discussed below.

- In many environments that have been tested, fibers are the most common type of MP found, and they have been judged to be the most abundant MP in the ocean,[76] comprising as much as 35% of MP.[21] Fibers were found to be the most common type of MP in Lake Michigan water and sediments, with fibers comprising 45% of all particles in water samples.[77] A careful review showed that fibers were the second most common shape of MP in fresh and drinking waters.[15] Several studies show that over 900,000 microfibers can be released from a single wash of a 6 kg load of laundry containing acrylic garments.[78-80]

- Synthetic garments can release substantial amounts of microfibers to the air, even without laundering. One study suggests that average releases of microfibers to the air are similar or even greater than via laundering for the same garments.[81] Two-thirds of all textile items are now synthetic, mainly polyester, polyamide (nylon), and acrylic.[21] Research suggests that natural fabrics (e.g., cotton) release significantly more microfibers than do synthetic ones,[82] but they will biodegrade much faster.

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Over 900,000 microfibers can be released from a 6 kg load of laundry containing acrylic garments

6 kg = 13.2 pounds

Considering both plastics and natural small aquatic particles, removal can be as great as 95% for standard secondary treatment systems. Most of the MPs removed are transferred to sludge and may wind up in terrestrial systems if the sludge is used as fertilizer.

- Sources of plastic fibers, tire wear particles, and manufactured microbeads are straightforward to understand, and perhaps easier to manage. Harder to comprehend are the nearly infinite number of undifferentiated MPs that derive from the breakdown of macroplastics, and which enter the environment via several routes.

- Probably the best known of these pathways is wastewater treatment plants (WWTPs), which have been well studied. Microplastics' concentrations in raw wastewater range up to 3160 particles per liter.[83, 84] WWTPs are not designed to remove MPs, yet they are relatively effective at doing so, with efficiencies measured from 63%,[80] to 64%,[85] and even up to 90%[54, 86] or 99%.[87]

- Considering both plastics *and* natural small aquatic particles, removal can be as great as 95% for standard secondary treatment systems.[88] Most of the MPs removed are transferred to sludge[83, 85] and may wind up in terrestrial systems if the sludge is used as fertilizer.

- Fibers and fragments were the two most common forms of MPs observed.[22, 84] Taken together, these studies suggest that WWTPs are a significant, but probably minor, source of MPs to the aquatic environment, and that MPs are efficiently transferred to sludge (also called biosolids), whose fate should be carefully monitored.

- Research on WWTPs seems to indicate that nonpoint sources and storm runoff are probably much greater sources of plastic and MPs.[87, 89] Unfortunately, our understanding of this source is limited, with very little research yet on MPs in stormwater or urban runoff. It is also true that freshwater and terrestrial MPs have received much less attention than marine ones. Freshwater sites can be challenging to study because of enormous variations over time at individual sites (up to a factor of 100 million).[90]

- But stormwater both contains higher levels of MPs than treated wastewater[91] and represents a much larger volume. Even perhaps more important, stormwater carries the vast majority of macroplastics, and these are the ultimate source of most MPs. This conversion is well known to be occurring in soils,[92] in the ocean,[93] and along its margins.[94, 95]

In the ocean, abandoned and lost fishing gear (ghost nets) are known to be a significant source of MPs. Likewise, waters in the vicinity of mariculture facilities show elevated levels of MPs.

- In agricultural soils, plastic mulch is known to be converted to MPs.[96] Sewage sludge is the repository for the majority of wastewater MPs (1,000 – 24,000 items per kilogram),[97] and half of it is currently used for agriculture. This constitutes a troubling level of soil contamination with MPs.[98, 99]

- In the ocean, abandoned and lost fishing gear (ghost nets)[100] are known to be a significant source of MPs.[101-103] Likewise, waters in the vicinity of mariculture facilities show elevated levels of MPs.[104]

- Taken together, multiple kinds of MPs – fragments, fibers, TWPs, nurdles, and microbeads – come from numerous sources, including personal care products, sewage treatment plants, and fishing gear. They wind up contaminating all parts of our environment, as will be detailed in the next section.

Remarkably, the whereabouts of the overwhelming majority of plastic estimated to enter the environment are unknown. For example, less than 1% of the 150 MT of plastics believed to have been released into the oceans over time have been located.

- Since the 1950s, an enormous amount of petroleum and natural gas has been used to generate plastics, most of which has ended up in the environment.
- A total of 8.3 billion metric tons (MT) of plastic waste was produced, of which less than 9% has been recycled, 12% incinerated, with the remaining 79% either going to landfills or being released to the natural environment.[105]
- Remarkably, the whereabouts of the overwhelming majority of plastic estimated to enter the environment are unknown.[106] For example, less than 1% of the 150 MT of plastics believed to have been released into the oceans over time have been located.[105]
- Three fates of the world's missing plastics have been proposed: (1) deposition in riverine and estuarine sediments and along shorelines; (2) settling of dense plastics into the deep-sea; and (3) fragmentation into microplastics (MPs) and nanoplastics (NPs) that are difficult to measure with today's techniques.

- For plastics and MPs that can be identified, a great deal of research has gone into documenting where it is found. This includes oceans and their beaches, estuaries, rivers and lakes, land and groundwater, drinking water, soils, and air, both indoors and in cities.
- Globally, plastics are ubiquitous.[107] They are found in all ecosystems and at all trophic levels of food webs.[37] Microplastics are found on the highest mountains[108] and the deepest ocean trenches.[109] They have been documented in the Arctic[110, 111] and Antarctic,[112-114] where they may be especially problematic because other kinds of pollution are rare.[115]
- Microplastics were identified and characterized from a remote crater lake at 2,380 m altitude in Erzurum, Turkey,[116] and at the Great Barrier Reef World Heritage site.[117] In every country that researchers have looked they have found MPs. This includes, for example, Brazil,[118] China,[119, 120] Canada,[121] as well as the Atlantic,[122] Northern Pacific,[123] Mediterranean,[124] Adriatic,[125] and Indian Oceans.[126]
- The distribution of plastics is global, but generally more is found near populated areas than elsewhere. For example, there is generally more in the Mediterranean than most of the Pacific.[127] Geographically, the five heaviest plastic polluters are China, Indonesia, the Philippines, Vietnam, and Sri Lanka, which together contribute more than half of global plastic waste.[105] Some of the plastic pollution from the countries named above has been imported from other countries. Still, what causes the observed spatial distribution remains poorly known. Microplastics are so ubiquitous that one study that found an exception (its nondetection in fur seal scats in Antarctica) judged the absence to be unexpected and notable.[129]

Ocean/Beaches

- Much of the earliest research on MPs was set in the world's oceans, and these systems have been studied most extensively.[119, 130] Perhaps the earliest documented occurrence of MPs in a marine system was for Long Island Sound (Connecticut). Researchers found levels up

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to 14 spherules per cubic meter in 1972.[131] Since that time, MPs have been studied and documented in all parts of the world's oceans,[28, 132-135] and there are over 2000 studies on MPs in the sea.

Microplastic levels vary substantially in fresh waters, though many investigators report high levels.

- Microplastics on beaches are similarly well-studied, with over 800 investigations to date, all showing that MPs are found on beaches worldwide. The high energy environment caused by waves and backwash make it especially likely that macroplastics will be converted to MPs in this environment.[136] Even plastic additives, like BPA,[137] UV stabilizers and brominated flame retardants,[138, 139] and metals* used in pigments (Al, Zn, Ba, Cu, Pb, Cd, Mn, Cr)[140] have been found in abundance on beaches.

Estuaries and Coastal Ecosystems

- World estuaries have also been well-studied, with MPs found universally in multiple systems from China[141] to Australia,[142] Africa,[143, 144] India,[145] Europe,[146, 147] South America,[148] and the U.S.[149, 150]

- Some other coastal ecosystems are less well-studied than estuaries, but microplastics are found in mangrove forests[151, 152] and coastal wetlands.[153] Microplastics seem to be especially effectively trapped by eel grass[154] and turtle grass,[155] and it has even been proposed that seagrasses provide an important ecosystem service by efficiently removing MPs.[156] Corals may be especially vulnerable to MP pollution, as they ingest many particles in this size range,[157] and can even incorporate them into their aragonite hard structures.[158] As is true for the ocean at large, MPs are found even among corals of remote, uninhabited islands.[126, 159]

***Metal elements**
Al = Aluminum
Zn = Zinc
Ba = Barium
Cu = Copper
Pb = Lead
Cd = Cadmium
Mn = Manganese
Cr = Chromium*

Fresh Waters/Rivers

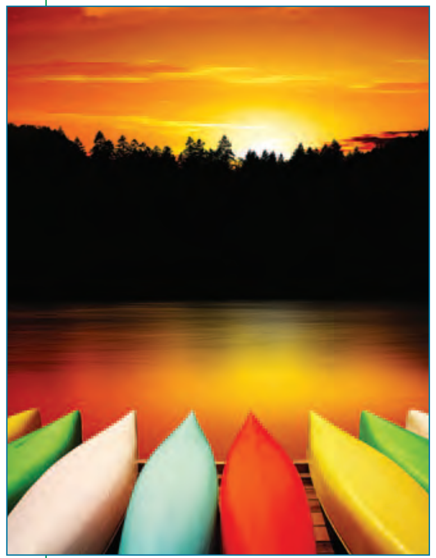
- Though oceans have received by far the greatest attention, there is rapidly increasing research on fresh water rivers and lakes. This is timely, because rivers are probably the major source of plastics to the ocean, accounting for 1.2 to 2.4 million MT annually.[160] The top 20 polluting rivers, mostly Asian, account for two-thirds of

the global total. Microplastic levels vary substantially in fresh waters, though many investigators report high levels. One study of three tributaries to Lake Michigan found averages of 2,600, 30,000, and 90,000 MPs per cubic meter.

Though oceans have received by far the greatest attention, there is rapidly increasing research on fresh water rivers and lakes.

- This is similar to results (all in units of MP particles per cubic meter) for several Chinese rivers: 700 to 24,000 (Shanghai river system),[161] 300 to 4,000 (Fenghua River),[162] 1,500 to 20,600 (Yangtze tributaries),[163] 800 to 27,000 (Nanfei River)[164] and 1,090 to 16,000 (Songhua River).[165]

- Some other studies have reported lower levels, for example, the Zhangjiang River in China averaged only 246 MP particles per cubic meter.[166] This is similar to results for the Ottawa River, Canada, which ranged from 50 to 240 MP particles per cubic meter near shore.[167] These researchers also documented an increase in MPs going from upstream to downstream of a sewage treatment plant. This differs from another study that found no simple relationship between microplastics and either population density or proximity to wastewater treatment sites.[168] Still, these authors considered rivers to be a hot spot and critical transfer pathway for MPs in the environment.



The sources of MPs in rivers are not yet fully established. In some cases, it could be from treated sewage, but the contributions from storm drains are not well studied and could be huge.

- It is not yet clear whether concentration ranges measured in various rivers are caused by real differences or dissimilarities in methods or the size range of MPs measured. It is well established that MP numbers increase as size decreases, sometimes exponentially, as shown in one recent review of MPs in freshwaters.[130]
- The sources of MPs in rivers are not fully established. In some cases, it could be from treated sewage, but the contributions from storm drains are not well studied and could be huge.[169, 170] Fragmentation of macroplastics in litter has also not yet been quantified adequately.

Drinking Water

- Of greatest interest to humans for environmental distribution is MPs in drinking waters and their sources. A critical review of the research literature found that levels ranged from 0.01 to 100,000,000 MPs per cubic meter in different systems.[15]
- Again, methodological differences may explain part of this enormous variation. If it is caused by size differences, the higher numbers are more probably correct, as methods that only detect larger MPs will undercount totals. These reviewers also confirmed the often published finding that polypropylene (PP) and polyethylene (PE) were the two most common plastic polymers.
- The results of frequently high MP levels are both alarming and widespread globally. One study showed that 83% of tap waters from six regions on five continents contained MPs ranging up to 57,000 MPs per cubic meter.[23] In China, 38 tap water samples taken in different cities averaged 440,000 MPs per cubic meter, with smaller particles (less than 50 microns) most abundant.[171] In Brazil, 32 samples of tap water from different locations averaged 158,000 MPs per cubic meter, with most in a size between 6 and 50 microns.[172]

Measurements
Micrometers (µm) are also known as microns

1 cubic meter (m^3) = approx. 35 cubic feet (ft^3)

- There is evidence that MPs can be partially removed during treatment of drinking water. Purification of potable water can take many forms, so it is hard to generalize. But one study found removal rates of from 25% to 83%, depending on MP type and specific treatment system.[173] Another study found removal rates of 63% and 85% for two different techniques.[174]
- Despite these encouraging results, it should be remembered that treatment can still leave thousands of MP particles, plus other MPs can be added between treatment and delivery at the tap. In fact, all of the tap waters tested and described above had received some kind of purification before measurement.

People often turn to bottled water when they suspect the presence of contaminants in their tap water. But most bottles are made from plastic, and many studies have shown that MPs and plastic additives are present in abundance there as well.

Bottled Water

- People often turn to bottled water when they suspect the presence of contaminants in their tap water. But most bottles are made from plastic, and many studies have shown that MPs and plastic additives are present in abundance there as well.

The problem of MPs in bottled waters is widespread geographically. Eleven brands of bottled water, purchased from 19 locations in nine different countries, were tested for microplastic contamination. Of the 259 total bottles evaluated, 93% showed some sign of microplastic contamination.

- For example, one study found that bottled water contained an average of 10,000 microplastic particles per liter.[175] The researchers concluded that the source for the MP particles was composed of PP and PET, which are major ingredients of bottle caps. The problem of MPs in bottled waters is widespread geographically.

- Eleven brands of bottled water, purchased from 19 locations in nine different countries, were tested for microplastic contamination. Of the 259 total bottles evaluated, 93% showed some sign of microplastic contamination. Even after taking into account possible lab contamination, an average of 10.4 microplastic particles per liter were found in the larger size fraction (> 0.1 mm).[176]

- Including smaller particles (6.5 to 100 µm), an average of 325 microplastic particles per liter were measured. Microplastic contamination ranged up to 10,000 MP particles per liter, with 95% of particles between 6.5 and 100 µm in size. This emphasizes the need to test for smaller MPs, which is difficult and infrequently done.

- Other investigators tested the microplastic content of water from 22 different returnable and single-use plastic bottles, as well as three beverage cartons and nine glass bottles obtained from grocery stores in Germany.[177] They found that small (50-500 µm) and very small (1-50 µm) microplastic fragments were present in every type of water.

- Importantly, almost 80% of all microplastic particles found had a particle size between 5 and 20 µm. They were therefore not detectable by the analytical techniques used in many previous studies.

- Perhaps surprisingly, MP levels were high even in glass bottles, ranging up to 253 particles per liter. This implies that at least some of the MPs derive from sources other than the bottles themselves.

- Sometimes, studies have been criticized for lack of quality control measures. But even when careful blanks were run and researchers worked in a filtered air environment, MP contamination has been found.[178] When 32 samples were investigated using rigorous quality control, water from all bottle types was found to be contaminated with microplastics. Again, high levels of MPs were detected even in glass bottles, suggesting sources in addition to the container.

- The level of microplastics varied from an average of 2,600 per liter in single-use PET bottles up to 6,300 per liter in glass bottles. Over 95% of the plastic particles were smaller than 5 µm, and about 50% were smaller than 1.5 µm.

- In plastic bottles, the predominant polymer type was PET. In glass bottles, various polymers such as polyethylene or styrene-butadiene-copolymer were found. One possible explanation for MPs in glass bottles is that they come from the cap rather than the container itself. Research shows that, even when plastic bottles were put under

One possible explanation for MPs in glass bottles is that they come from the cap rather than the container itself. Research shows that stressed plastic bottles do not release MPs from the container, but they do from the cap.

In addition to the plastic polymers and MPs themselves, there are numerous additives in plastics used to manufacture bottles, which can leach out into the drinking water.

stress by being repeatedly squeezed, they did not show MP coming from the bottles themselves, but from their plastic tops.[179] Investigators tested single-use PET mineral water bottles with caps made from high-density polyethylene (HDPE), a common combination. They exposed the bottles to mechanical stress by squeezing them, and tested the caps by opening and closing them multiple times.

- There was a substantial increase of MP particles composed of PET and HDPE on the bottlenecks and caps after opening and closing the bottles. The release of MPs continued through at least 100 such cycles. Perhaps surprisingly, squeezing the bottles did not have a significant effect in releasing MPs.

- Working with new, and somewhat controversial, methods,[180, 181] one group of researchers was able to measure even the smallest size MPs and found extraordinarily high levels, averaging 54 million particles per liter.[182]

- Microplastics were found in every one of 10 nationally distributed Italian water bottle samples tested. Based on their data for mineral water, they estimated that the daily intake for adults and children were 1,530,000 and 3,350,000 MPs per kg bodyweight/day, respectively,[182] pointing to the possibility of enormous levels of MPs that may be ingested from bottled waters.

Plastic Additives and Bottles

- In addition to the plastic polymers and MPs themselves, there are numerous additives in plastics used to manufacture bottles, which can leach out into the drinking water. Here we consider just two categories, both of critical concern for human health: bisphenols and phthalates.[183]

- Bisphenol A (BPA) is an endocrine-disrupting compound (EDC) with estrogenic activity. It is widely used in the production of plastics and has been shown to be released into bottled waters.[184] Although uncertainties remain, the endocrine disrupting activity of BPA and its effects on reproductive health have been widely studied.

- Phthalates are also EDCs used as plasticizers in many products. Because these compounds are weakly bound to the plastic polymers, they leach out from it relatively easily, leading to potentially high human exposure.

- Phthalates have been shown to occur in the microgram per liter level in bottled water.[185] Contact with bisphenols and phthalates during human development affects important immune system components and functions. It has been suggested that they are related to the development of several diseases, including cancer.[183]

- Animal studies have documented a variety of endocrine effects of BPA.[186] In humans, higher urinary concentrations of BPA have been found to be associated with diagnoses of cardiovascular disease and type-2 diabetes.[187]

Contact with bisphenols and phthalates during human development affects important immune system components and functions. It has been suggested that they are related to the development of several diseases, including cancer.

Endocrine-disrupting compounds are of special concern because of their widespread use (including in plastic water bottles) and links to negative human health outcomes.

- Similar association of higher urinary BPA concentrations with heart disease is based on data from the National Health and Nutrition Examination Survey (NHANES) 2003-2004 and NHANES 2005-2006, independent of traditional risk factors.[188] Separately, a study of a large group of NHANES participants showed that BPA was measurable in the urine of 93% of the 2,517 people tested.[189]

- Endocrine-disrupting compounds are of special concern because of their widespread use (including in plastic water bottles) and links to negative human health outcomes. The persistent and long-term use of EDCs has deleterious effects on human reproductive health by interfering with the synthesis and mechanism of action of sex hormones, thereby impacting male reproductive health.[190]

- The EDCs bisphenol and phthalates have received the greatest attention, but many other plastic additives are known to leach from bottles into the water they contain.[191]

- This includes substances ranging from DEHP (di(2-ethylhexyl)phthalate)[192] and its breakdown products (believed to be more toxic than DEHP itself) to formaldehyde, acetaldehyde, and antimony.[193]

- Evidence for harmful health effects on humans from exposure to these substances known to be released from plastic water bottles is incomplete, but data are sufficient to suggest that limiting exposure is warranted.[186]

***DEHP** = (di(2-ethylhexyl)phthalate)*
***PP** = polypropylene*
***Ps** = polystyrene*

Soils and Land

- The terrestrial environment of soils has been poorly studied compared to marine and fresh waters, though several reviews of the existing research have appeared recently.[198, 199] Of greatest concern are agricultural soils, where there is a possible link to the food web for humans.[199] Sewage sludge, sometimes called biosolids, as well

as plastic film mulch, are commonly used as agricultural soil amendments. High levels of MPs in biosolids are not surprising considering that during wastewater treatment, over 90% of MPs are retained in sewage sludge.[200]

High levels of MPs in biosolids are not surprising considering that during wastewater treatment, over 90% of MPs are retained in sewage sludge.

- In Europe, from 125 to 850 g of MPs per capita are added to farmland soils through application of biosolids.[99] This amounts to between 63,000 to 430,000 MT added each year in Europe alone, with similar amounts in the U.S. Taken together this is more than the accumulated amount of MT floating in the world's surface oceans.[201]

- The path of MPs from sewage to sludge to farmlands to plants to people is very poorly understood. It has been pointed out that lack of evidence of ecological impact from microplastic and nanoplastic in agroecosystems does not equate to the evidence of absence,[202] and further research is required.

Groundwater

- So far there has been very little research on MPs in groundwater. It appears that Karst groundwater (the kind found in limestone) can contain modestly high amounts, up to 15.2 MPs per liter, mostly fibers.[203]

- MPs co-occurred with other contaminants and were attributed to septic effluent. One study of groundwater near landfills in India found numerous MP particles, which were attributed to buried plastics and waste fragmentation, and which were predominantly polypropylene (PP) and polystyrene (PS).[204]

- Some MPs were found in groundwater in Poland.[205] Two studies found that MP levels were low in groundwater used for drinking water supplies.[206, 207] This is consistent with natural filtration that takes place in the subsurface, and lower total suspended solids that are found there.

Air

Indoor MPs are inhaled, but they can also be ingested, especially if they fall on food items. It appears that amounts of MPs ingested in this way may be vastly greater than from those in the original foodstuff.

- Inhalation is a known uptake pathway for MPs by humans, so distribution in air is important. MPs have been found everywhere in air that investigators have looked. MPs tend to be higher near population centers, and greater indoors than out.

- One approach is to measure MPs in fallout (settling particles) and the dust it generates. In Chinese buildings, MP deposition ranged from 1,500 to 9,900 MPs per square meter per day, varying with building use, and higher in a dormitory than office or hallway locations.[17]

- Most MPs were fibers similar to the textiles in use, and air movement could stir up the MPs. The researchers calculated that intake by infants would be between 4 and 150 micrograms per kg of bodyweight per day. Other investigators in Paris reached similar conclusions: a preponderance of fibers in indoor locations, as well as variations depending on room uses. Indoor deposition ranged between 1,600 and 11,100 fibers per square meter per day.[208]

- Outdoor levels were much lower, and declined from more urban to suburban locations.[209] Still, the researchers estimated a deposition of between 3 and 10 tons of fibers by atmospheric fallout in the Paris region each year.

- Indoor MPs are inhaled, but they can also be ingested, especially if they fall on food items. It appears that amounts of MPs ingested in this way may be vastly greater than from those in the original foodstuff.

- For example, mussels have been widely measured, and an estimated 123 to 4,600 MPs per year might be ingested from this source. But fiber exposure during meals from dust fallout is calculated to be between 13,700 and 68,000 particles per person per year.[210]

MP levels are generally greater closer to population centers, where airborne MPs can be generated from sources like tire wear and fragmentation from textiles.

- Outdoors, MPs have been measured in air from Paris[209] to Tehran[211] to Chinese cities[212-214] to Hamburg.[215] MPs have even been measured in air at remote locations like the Pyrenees[216] and the Alps,[217] as well as remote Atlantic[218] and Pacific sites[219] and up to at least 3.5 km (2.2 miles) above the ground.[220]

- It is hard to compare the amounts of MPs in air because different researchers use different units to measure MPs. Some measure the amount in the air or settled onto surfaces, while others measure the amount contained in dust.

- MP levels are generally greater closer to population centers, where airborne MPs can be generated from sources like tire wear[68] and fragmentation from textiles.

- MPs in the air can be directly inhaled[212] or ingested as dust[211] or on food items.[210] Indeed, inhalation[212] and plastic water bottles are considered the two major routes of human exposure to MPs.[221]

8. The Behavior of Plastics in the Environment

Probably the single most substantial pathway of mismanaged waste plastics in the environment is from land to sea, carried by rivers.

- Once in the environment, plastics are transported by water and wind, they degrade to smaller pieces (and perhaps are biodegraded). They take up and carry toxic chemicals and pathogens, and they may enter the food web.

Transport/Movement

- Probably the single most substantial pathway of mismanaged waste plastics in the environment is from land to sea, carried by rivers. Eventually some of the plastics sink to the bottom and may become buried in sediments.[222]

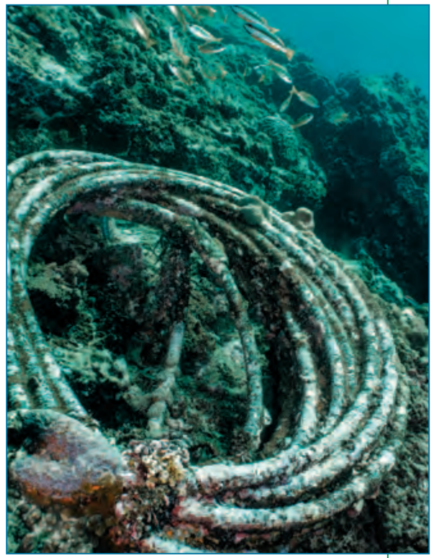
- Packaging and consumer products make up most of the plastics in rivers, while discarded and lost fishing gear are also added directly to the ocean. It turns out that plastics from other sources, like electronics, building and construction, and transport are rare. Among the various polymers, polyethylene and polypropylene are most common in all environments.[222]

- One early study proposed that small microplastics are likely to settle slowly from the water column and to be transported by the flow of water and deposited where the movements of water are slower.[223]

- Indeed, microplastic abundance varies geographically, with locations, hydrodynamic conditions, and time.[224] It has also been proposed that transport and ultimate distribution are influenced by marine organisms, for example by ingestion and the production and settling of fecal pellets.[128]

- Several studies have tried to model MP transport in the environment,[225-228] but there is a lack of hard data, and the relative importance of various transport processes remains uncertain.

- Microplastics can also be carried to remote locations by winds, and there is evidence that this may be as great as transport by rivers, at least for certain locations and MP types.[229]



Packaging and consumer products make up most of the plastics in rivers, while discarded and lost fishing gear are also added directly to the ocean.

Degradation/Decomposition/Fragmentation

- Plastics are known to be resistant to degradation, but the very existence of secondary MPs (those that are not intentionally manufactured, like microbeads) is strong evidence of at least a physical breakdown over time.

- Indeed, degradation of plastic bottles occurring with a half-life of as little as 58 years was indicated in one study.[230] More massive plastics (like pipes) were expected to degrade only over many hundreds of years.

- UV light, including that in sunshine, is known to degrade many materials, including plastics. Several recent studies show this occurs, albeit slowly for several plastic polymers in various environments, from air to fresh and salt water.[231, 232] Mechanical properties were affected, causing a weakening of the material, which became less

It is widely believed that plastics in the environment persist for centuries. For example it has been asserted that plastic bag breakdown takes 1000 years. But some lab studies suggest that degradation may occur more rapidly.

***LDPE** = low-density polyethylene*

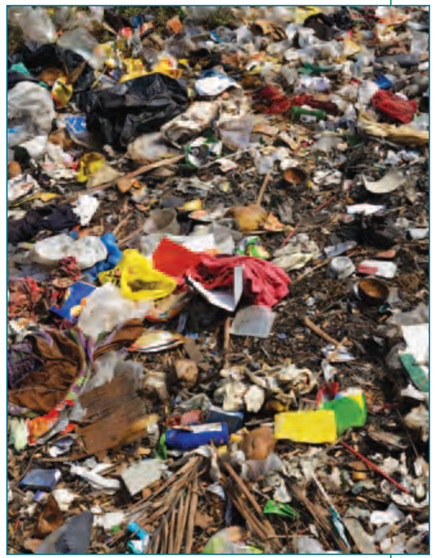
***PE** = polyethylene*

***PS** = polystyrene*

elastic and more rigid. Scanning Electron Microscope (SEM) images showed cracks and other physical degradation.[13] Of course, UV degradation requires that the plastic remain in sunlight for extended periods of time, usually as unsightly waste materials.

Breakdown of Plastic by Microbes

- Breakdown of plastic by microbes[234] is an active area of research,[235] both to see if it occurs in nature and as a potential treatment technology.[236]
- It is widely believed that plastics in the environment persist for centuries. For example it has been asserted that plastic bag breakdown takes 1000 years.[237] But some lab studies suggest that degradation may occur more rapidly.
- One lab study isolated bacteria and fungi from marine sources. They found that polymers from plastic bottle waste showed 35% degradation using bacterial strains and 22% using fungal strains, in a time period of only six weeks.[238]
- Other researchers isolated four marine bacterial strains that were able to partially degrade LDPE.[239] The most efficient of these strains caused a 1.7% mass loss after 90 days of incubation.
- Macroplastics in landfills were found to be degrading when examined after five years.[240] Bacteria appear to thrive on the surface and develop a biofilm (slime layer formed from exuded substances). One negative outcome of bacterial degradation is that it appears to promote formation of MPs from macroplastics.
- For terrestrial systems, bacteria isolated from the gut of earthworms seem especially capable of degrading plastics. One study found that LDPE treated with these bacteria significantly reduced MP particle size and converted a substantial portion of the polymers to large dissolved molecules (relatively harmless alkanes). In total, there was a very substantial 60% mass loss.[241]
- Some insects are also believed to be able to crush plastics by gastric grinding and chewing, and also to change the chemical properties of the ingested plastics biochemically within their guts.[242] Several studies have found that at least one type of caterpillar larvae (greater wax moth) is able to degrade PE and PS, probably through bacteria they host.[243, 244]
- In summary, laboratory studies have reported several modalities of degradation by microorganisms on many types of plastic polymers, usually by enzymatic hydrolysis or oxidation.
- However, most common plastics have proven to be highly resistant to biodegradation, even when conditions are optimized to favor the microbes.[245] Our understanding of how effective these pathways might be in nature is very limited.



Macroplastics in landfills were found to be degrading when examined after five years. Bacteria appear to thrive on the surface and develop a biofilm (slime layer formed from exuded substances).

In one study, mussels were exposed to 0.5 µm fluorescent polystyrene microspheres, then fed to crabs. Microspheres were taken up by the mussels and transferred to the crabs.

Food web/Biomagnification

- The risk posed by a contaminant is greater if it can be bioconcentrated and transferred up food webs. Fortunately, at present, there appears to be little evidence for bioconcentration of MPs during trophic (food chain) transfer.[246]

- Research indicates that MPs bioaccumulate at as many as five different trophic levels, but do not multiply from one level to the next.[246] The exception to this pattern appears to be with the very smallest MPs, approaching the dimensions of nanoplastics.

- One study looked at *Daphnia* and fathead minnows, and found no transfer from prey to predator and no translocation out of the gut to other organs.[247] These results argue against bioconcentration or bioaccumulation, at least for this two-organism system.

- Similarly, research on the marine food web of the Persian Gulf did not find biomagnification of MPs in the edible parts of seafood and even suggested that microplastic trophic dilution occurs, rather than magnification.[248]

- However, others have found evidence of both translocation and trophic transfer. In one study, mussels were exposed to 0.5 µm fluorescent polystyrene microspheres, then fed to crabs. Microspheres were taken up by the mussels and transferred to the crabs.

- The microplastics were also found in the stomach, hepatopancreas, ovary, and gills of the crabs.[249] In another study, six different organisms at different trophic levels were exposed to 10 µm fluorescent polystyrene microspheres.[250] All of the tested groups of populations of organisms ingested the microplastics.

- Furthermore, food web transfer experiments with mysid shrimp revealed the presence of zooplankton prey and microspheres in the shrimps' intestines after three hours. Plankton are organisms that drift in oceans and other bodies of water. This shows transfer of microplastics via planktonic organisms from one trophic level (mesozooplankton) to a higher level (macrozooplankton).

Clearly, nanoplastics are easily transferred through food chain. Other studies on nanoplastics have found similar results.

- The apparent lack of biomagnification and trophic transfer is clearly different for nanoplastics (particles smaller than 1 µm). One study documented transfer across four trophic levels from algae up to end-consumer fish.

- Furthermore, nanoplastics negatively affected fish activity, and induced histopathological changes in the livers of fish that were directly exposed. Additionally, nanoplastics penetrated the embryo walls and were present in the yolk sac of hatched juveniles.

- Clearly, nanoplastics are easily transferred through food chain. Other studies on nanoplastics have found similar results, e.g., from algae to *Daphnia* to fish.[251]

Research is needed to determine bioaccumulation factors for widely consumed seafood products to evaluate the potential impacts on human health.

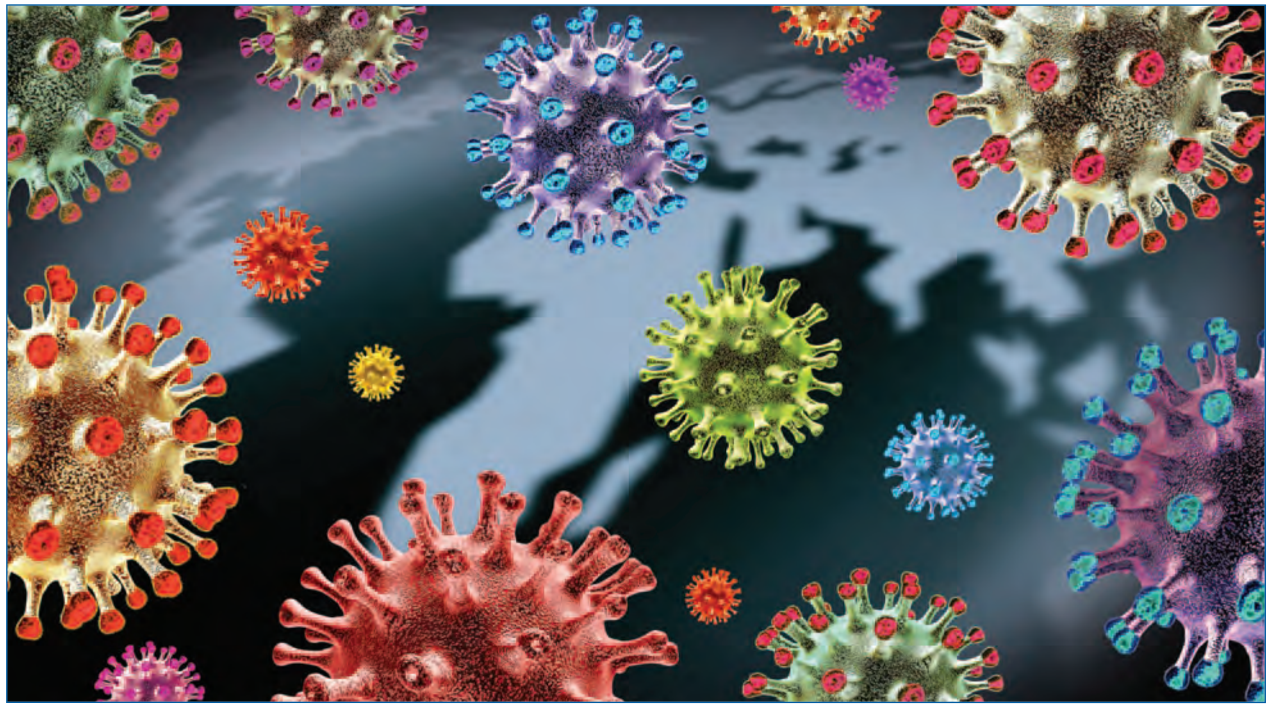
- In summary, the research on MP transfer through food webs and possible biomagnification remains equivocal,[252] even though many studies document MP uptake at multiple trophic levels.
- These trophic levels (groups of organisms) include:
  - Animals (including echinoderms, mollusks, arthropods, annulatas, cnidaria, mammals, birds, amphibians, reptiles, and fish)
  - Plants (including algae, gymnosperms, and angiosperms)
  - Microorganisms (including bacteria, fungi, and protozoa)[26]
- But there have not been attempts to track microplastics through complex marine food webs using environmentally relevant concentrations to identify the eventual real level of risk to people.
- Research is needed to determine bioaccumulation factors for widely consumed seafood products to evaluate the potential impacts on human health.[253]

Contaminant vectors

- Among the most worrisome environmental behaviors of microplastics is their tendency to attract, bind, and transport toxic chemical and microbes, including pathogens.
- This is in addition to additives that are intentionally included in the plastic formulation, such as bisphenols and phthalates. The tendency to concentrate and introduce harmful agents to organisms that ingest MPs has been called a Trojan Horse effect.[254-256]

Vectors for pathogens

- Microplastics have a large surface area per mass and provide a special microbial niche where bacteria and viruses can thrive.[257]



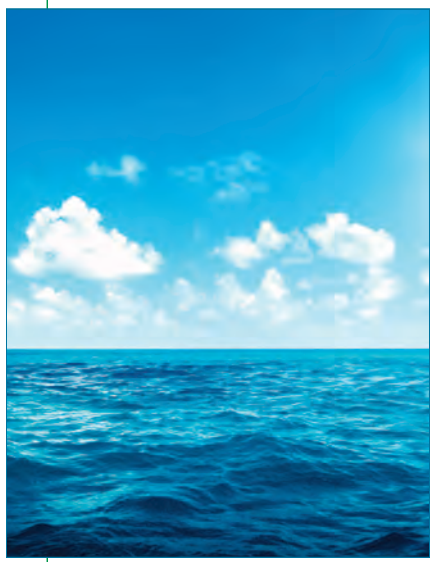
Bacteria are known to release special compounds (exopolysaccharides) to form a protective slime layer (biofilm) that promotes their ability to live on surfaces.

In air, rather than water, microplastics have even been implicated as a pathway for the spread of COVID-19.

- There is evidence that the slime layer on microplastics, sometimes called the plastisphere,[258] supports a distinctive microbial community structure[259] and carries organisms unlike those on particles of natural materials, like sediment or wood.[260]
- Studies on microplastics have shown that numerous potentially harmful organisms prefer to live in this environment. These include foodborne infectious species,[261, 262] fish pathogens,[263] as well as *E. coli* and related bacteria,[264] human pathogens,[259] and antibiotic-resistant genes (ARGs).[260, 265]
- In air, rather than water, MPs have even been implicated as a pathway for the spread of SARS-CoV-2 (COVID-19).[266]

***Plastiphere** refers to the biological environment, including the slime layer, immediately adjacent to microplastics.*

***Ecocorona** is a similar term for the region around microplastics, but with more emphasis on chemical, rather than biological, processes.*



The persistent organic pollutants (POPs) are of special concern. Unlike inorganic particles that occur naturally in sea water, microplastics concentrate POPs by several orders of magnitude (factors of ten) onto their surfaces.

Vectors for chemical contaminants

- Just as there can be a plastisphere of biofilm that harbors pathogens around MPs, it has been suggested that an ecocorona of organic matter and contaminants can surround MPs and allow toxic substances to build up.[28, 267]

- The preferential adsorption of contaminants to MPs could allow the particles to gather and concentrate toxic substances, and then deliver them to organisms at elevated levels.[268, 269]

- The persistent organic pollutants (POPs) are of special concern. Unlike inorganic particles that occur naturally in sea water, microplastics concentrate POPs by several orders of magnitude (factors of 10) onto their surfaces.[270]

- As a result, microplastics may serve to increase POP uptake when ingested by marine organisms. It has been suggested that the concentration factor can be as great as 1 million times the pollutant level in surrounding waters.[271]

- This concentration suggests that ingestion of MPs can be a possible pathway for the introduction and biomagnification of toxic chemicals in the marine food web. Similar results also appear to apply to toxic metals, like copper, zinc,[272] cadmium, and lead,[273] although they have been studied much less.

- In addition to serving as a pathway for uptake and toxicity by organic contaminants and metals, MPs may serve to facilitate transport of harmful substances through air, water, or soil.[274, 275]

- Microplastics carrying toxic substances like DDT and hexachlorobenzene can wind up in bodies of water, traveling all the way from rivers to oceans,[276] or in air currents traveling around the globe.[277]

9. Ingestion and Inhalation of Microplastics

Microplastics in the environment can be a health concern for humans only if they are taken up by ingestion of foods and beverages, or from the air via inhalation.

- Microplastics in the environment can be a health concern for humans only if they are taken up by ingestion of foods and beverages, or from the air via inhalation.

- Several studies have tried to assess human uptake across all these sources and routes. Results vary substantially depending on data sources, though estimates have tended to rise over time as growing numbers of smaller MPs have started to be detected.

- One group of researchers evaluated microplastics in 159 globally distributed tap waters, 12 brands of beer, and 12 samples of table salt. They calculated that the average person ingests over 5,800 MPs from these three sources annually, with most coming from tap water (88%).[278]

- Another group summarized 26 studies that measured over 3,600 samples. They concluded that microplastics consumption ranges from 39,000 to 52,000 particles per person per year, depending on age and gender. Adding inhalation as an uptake source increased estimates to between 74,000 and 121,000 per year.

Furthermore, if individuals drank only bottled water, they would be ingesting an additional 90,000 MPs annually, though an increase of only 4,000 MPs if imbibing only average tap water.

- Furthermore, if individuals drank only bottled water, they would be ingesting an additional 90,000 MPs annually, although only 4,000 more MPs if imbibing only average tap water.[279]
- The investigators acknowledged the variability and uncertainty of the estimates, but believed that their values were most likely to be underestimates.
- Still another, more recent, study estimated that the total human exposure to MPs is 3×10^{10} (30 billion) particles per year, from combined ingestion, inhalation, and dermal contact routes, but mainly from ingesting fruits, vegetables, and water.[280] These researchers were troubled by the enormous variability in existing data and called for better, more standardized methods.
- Considering these probably enormous numbers, it is worthwhile to look at some of the individual foodstuffs that are responsible. Ordinary table salt has been found to contain MPs at levels up to at least 13,600 MPs per kilogram. One study summarized results for 128 brands of salt from 38 different countries spanning over five continents,[24] finding MPs ubiquitous.
- Microplastics are also present in commercially available beer, honey, sugar, and mussels,[18] as well as many other forms of seafood described below. Indeed, most previous studies have been done on aquatic environments, but terrestrial earthworms, chickens, and birds all show uptake of chemicals from ingested plastics.[202, 281, 282]
- An analysis of many studies found that more than 200 animals used for food contain MPs.[283] Similarly, it has been shown that an edible plant (lettuce) can take up very fine MPs through its roots.[284]

Numbers of MPs vary depending on the source of the organisms, the species analyzed, and the methods used, but MPs are virtually ubiquitous in both marine and freshwater animals.

- MPs have been measured in both beer[285] and wine,[286] though so far at low levels (100s of MPs per liter). For wine, it is possible, though not certain, that the MPs come from polyethylene plastic stoppers, since no natural cork-stoppered wines have yet been tested.[287]
- One somewhat controversial study concluded that billions of MPs were released from each synthetic teabag.[288] But even the study refuting that extremely high result acknowledged that at least tens of thousands of microplastics in the size range greater than 1 µm were released from synthetic tea bags.[289]
- The single biggest food category that has been tested is seafood, both finfish and shellfish. Numbers vary depending on the source of the organisms, the species analyzed, and the methods used, but MPs are virtually ubiquitous in both marine and freshwater animals. For example, microplastics were found in 323 of 494 total species, and 262 of 391 commercial species that were tested.[290, 291]

Microplastics have been measured in the muscle, such as fish filet, and in processed (canned) fish originating from 13 countries over four continents.

- Considering that MPs have been measured in essentially all waters tested and in many prey species (like zooplankton),[292] it is natural that MPs are also found in the digestive tract of aquatic organisms.[293]

- Several studies have reviewed the many investigations that have found MPs in fish,[264, 294] including those in markets intended for human consumption.[295, 296] Microplastics have been measured in the muscle, such as fish filet,[248] and in processed (canned) fish originating from 13 countries over four continents.[297]

- Based on results of this kind, annual uptake by humans from fish has been estimated to be between 11,000 MP particles[298] and 55,000 MP particles per year.[299]

- Ingestion by way of seafood organisms would not be of concern if MPs were restricted to the digestive tract, which humans rarely eat, except in the case of some shellfish, which are eaten whole.

- However, there is considerable evidence that MPs (especially smaller ones) translocate into many organs from the gut of several organisms, including ones used for human food. These include the skin, muscle, gills and liver of:
  - demersal fish (living near the bottom)
  - pelagic fish (living in open water)
  - the tiger prawn[300]
  - the lymphatic and circulatory system of mammals[301]
  - the liver of wild fish near Paris[302]
  - European anchovy
  - European pilchard
  - Atlantic herring[303]
  - the circulatory system of mussels[304]

- Perhaps even more concerning is the growing evidence that smaller MPs can even cross cell walls.[305, 306] Indeed, MPs have been used as one means of drug delivery for years.[307] One study showed that MPs that are altered in the environment can undergo cellular internalization into macrophages (a type of white blood cell).[308]

- Cellular internalization has also been documented for the blue mussel after an experimental exposure.[309] Much more research is needed on this topic.

Water

- A great deal of evidence shows that significant human uptake of MPs occurs through drinking water, from the tap and especially in bottles.

- One study analyzed 159 samples of tap water from around the globe and found anthropogenic particles (pollutants from human activity) in 81% of them, ranging up to 61 particles per liter.[278]

- Other researchers reviewed seven studies and found levels ranging from very few to more than 4,000 microplastic particles per liter.[310]

A great deal of evidence shows that significant human uptake of MPs occurs through drinking water, from the tap and especially in bottles.

With initial levels as high as 100,000 MPs per liter, even 90% removal can only lower MP levels by about a factor of ten. This explains the still high levels measured at the tap, where water has always undergone some form of pre-treatment.

This variability, noted in many studies, is usually attributed to differences in the size ranges measured, with small particles being much more abundant.

- A similar result was found in three drinking waters from various sources (338 to 628 microplastic particles per liter).[311]

- Two studies reviewed existing research and narrowed results down to the few with the best quality control measures. Danopoulos and co-workers[312] used 12 "studies that used procedural blank samples and a validated method for particle composition analysis."

- The maximum reported levels were 628 and 4,889 MPs per liter for European tap and bottled waters, respectively. Based on typical consumption data, these results extrapolate to a maximum yearly human uptake of 458,000 MPs for tap water and 3,569,000 MPs for bottled water.

- A similar study selected four out of 50 studies based on quality criteria, concluding that MPs are frequently present in freshwaters and drinking water, with levels ranging up to 100,000 per liter, but with large variability.[15] The presence of MPs in drinking water raises the question of the effectiveness of standard treatment methods to remove these particles.

- A broad range of purification technologies have been compared: coagulation combined with sedimentation and granular activated carbon,[313] sand filtration (78% removal), reverse osmosis, ozonation, carbon filtration,[314] coagulation/flocculation, flotation, membrane processes, chemical or biological digestion, biodegradation, wet oxidation, and advanced oxidation processes.[315]

- Removal efficiencies ranged from 40 to 80% and even higher. Notably, none of these methods has the specific goal of removing MPs, but represent standard drinking water treatment approaches

One of the earliest studies showed that the shore crab (Carcinus maenas) can take up microplastics through inspiration across the gills.

that are currently used almost universally in developed countries. However, with initial levels as high as 100,000 MPs per liter, even 90% removal can only lower MP levels by about a factor of ten.

- This explains the still high levels measured at the tap, where water has always undergone some form of pre-treatment. It also implies that community drinking water treatment is not a solution to MP pollution.

Inhalation

- Another pathway for microplastic uptake is inhalation via the lungs, or by analogy, in fish through the gills. Both uptake routes have been documented.

- One of the earliest studies showed that the shore crab (Carcinus maenas) can take up MPs through inspiration across the gills.[316] As described earlier in this report, microplastics have been meas-

Microplastics have been measured in air from around the world. For example, MPs have been detected in atmospheric fallout in Greater Paris.

ured in air from around the world.[317-319] For example, MPs have been detected in atmospheric fallout in Greater Paris.

- Due to their small size, the MPs can be inhaled and might even induce lesions in the respiratory system.[320] Smaller MPs fall in the size range of easily respirable particles (usually called $PM_{2.5}$, or particulate matter up to 2.5 µm in effective diameter).
- Very fine MPs can be inhaled deep into the lungs, where they can cause asthma-like symptoms, or in the extreme case malignant cells.[321] Not surprisingly, MPs have been found in human lungs analyzed during autopsies.[322] A number of potential human health effects of inhaled MPs are described in the next chapter.

Transdermal uptake

- Although the possibility of transdermal (through the skin) uptake of MPs has been raised by several investigators,[280, 321, 323, 324] so far there seems to be no evidence or even research on this topic.

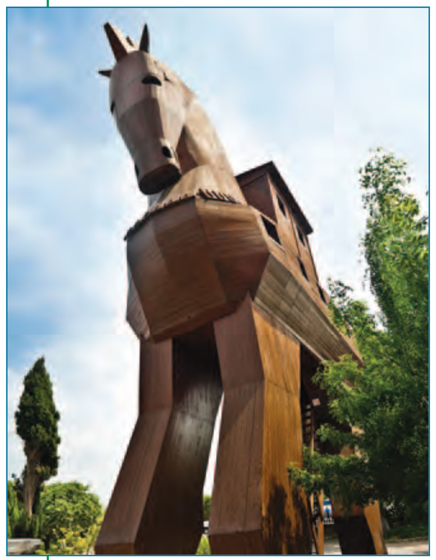
10. The Health Effects of Microplastics

How microplastics affect human health

- Although microplastics can cause impairment to a wide variety of animals,[325] plants,[326] and entire ecosystems,[28, 115, 327] probably the greater worry is that MPs can harm humans, either directly or through damage to gut microbiota.
- Microplastics are now known to be taken up in large numbers via both ingestion and inhalation, they are transferred to several organs, and they can cause numerous kinds of harms through multiple mechanisms.
- As with all human health research, ethical concerns limit the kinds of direct measurement methods that can be used to understand the impacts of MPs.
- Nevertheless, *in vitro* studies and those conducted on animal surrogates, as well certain kinds of direct evidence, strongly suggest that MPs are a potentially serious human health threat.[e.g., 9, 328]

MPs are now known to be taken up in large numbers via both ingestion and inhalation, they are transferred to several organs, and they can cause numerous kinds of harms through multiple mechanisms.

The gut microbiota *comprises over one hundred trillion microorganisms that colonize the intenstines of the human body.*



In what has been called a "Trojan horse effect," plastic debris adsorbs and concentrates ... many chemicals listed in the Stockholm Convention for their known direct human health effects.

The Stockholm Convention on Persistent Organic Pollutants (POPs) is a 2001 multilateral treaty to protect human health and the environment from POP chemicals.

Pathways

- As described in a previous chapter, human exposure to microplastics can occur through ingestion, inhalation, and perhaps even dermal contact, due to their presence in food, water, air, and consumer products.[329]

- Furthermore, MPs can cause harms through their constituent polymers, degradation products, chemical additives, or toxins and pathogens that are adsorbed onto their surface.[330]

- The MPs can come from sources that we normally trust, like bottled water,[331] baby bottles,[332] or breathing seemingly clean air.[333] Combined, these uptake pathways lead to large annual exposure. One survey of many research studies estimated that humans may ingest 0.1 to 5 grams (up to one teaspoon) of microplastics weekly through various exposure pathways.[334]

- Some virgin plastics which are composed of simple monomers, might by themselves pose relatively low risk. But we now know that MPs serve as carriers for a witch's brew of organic contaminants,[31] toxic metals, human pathogens, and antibiotic resistance genes (ARGs).

- In what has been called a "Trojan horse effect,"[256] plastic debris adsorbs and concentrates high levels of hydrophobic organic contaminants (HOCs), including PAHs, organochlorine pesticides, polychlorinated biphenyls,[274, 335, 336] metals (e.g., cadmium, lead, selenium, chromium),[272, 337, 338] metalloids,[339] and additives (e.g., bisphenol A, phthalates, and nonylphenols).[340]

- Many of these chemicals are listed in the Stockholm Convention for their known direct human health effects.[341] MPs have an abundant surface area that serves as an ideal environment for colonization by bacteria who shroud themselves in a protective biofilm.[342, 343]

- Through this mechanism, MPs have been shown in lab and fiel-studies to carry multidrug resistant opportunistic human pathogens like *M. morganii,*[344] potentially pathogenic bacteria (such as Enterobacter, Helicobacter and Arcobacter species), *Clostridium perfringens,* and *E. coli*.[345] MPs even carry genes[346, 347] that can aid bacteria in resisting antibiotics (ARGs).

Once taken up by inhalation or ingestion, most MPs are found in the lungs and digestive tract of humans.

Where in humans are microplastics found?

- Once taken up by inhalation or ingestion, most MPs are found in the lungs[322] and digestive tract[348] of humans. But there have been several studies demonstrating translocation to other organs of animals including mice (liver and kidney)[349] and fish (muscle and liver,[350] gill and gut).[351]

- Furthermore, evidence indicates that MPs can be found in the human placenta,[352, 353] the lymphatic system,[307] bloodstream,[354] and perhaps the liver.[355] Details of how translocation can occur in humans, via intestinal Peyer's patches and paracellular persorption have been described.[341] This could lead to transfer to the liver, muscles, and brain, though experimental proof does not yet exist. MPs from degrading plastic joints are known to circulate within the body to the liver and spleen.[356]

- Finally, it has been shown that nanoplastics can translocate across the human intestinal barrier,[357] so the question is, at what size along the microplastic-nanoplastic continuum does this become possible? Much more research is required on this topic.

What kinds of effects do microplastics have on humans?

- Once in the body — either the gut, lungs, or other organs — MPs can degrade human health through a variety of modalities, from toxicity to disturbance of the digestive systems' microbial biome.

***Peyer's patches** are part of the lymphatic system found in the small intestine.*

***Persorption** is the passage of tiny food particles through the lining of the gastro-intestinal tract.*

Among the most widely used polymers, PVC is worst in terms of its constituent monomer and common additives, including benzene, phthalates and lead stabilizers.

***The Globally Harmonized System of Classification and Labelling of Chemicals (GHS)** classifies the physical, health and environmental hazards of chemicals, and harmonizes labels and safety data sheets.*

- Because of the ethical limitations on doing research on people, much of what we know must rely on examination of other animals, *in vitro* investigations of how MPs and associated chemicals affect human cells, or studies of occupational exposure to MPs at very high levels.

- *Toxicity* is damage caused to an organism by a chemical substance. It can occur by a wide variety of mechanisms, including membrane disruption, extracellular polymeric substance disruption, reactive oxygen species generation, DNA damage, cell pore blockage, lysosome destabilization, and mitochondrial depolarization.[358]

- Several of the polymers used to fabricate plastics are themselves potentially toxic when they exist as monomers. One study considered 55 different thermoplastic and thermosetting polymers, evaluating their hazardousness under the EU classification, which is based on the UN Globally Harmonized System (GHS).

- The most hazardous (polyurethanes, polyacrylonitriles, polyvinyl chloride, epoxy resins, and styrenic copolymers) were made from monomers classified as mutagenic and/or carcinogenic (category 1A or 1B).

- Thirty-one out of 55 (including unsaturated polyesters, polycarbonate, polymethyl methacrylate, and phenol formaldehyde and urea-formaldehyde resins) are made of monomers that belong to the two worst of the five hazard levels, i.e., levels IV-V.

- All have a large global annual production measurable in millions of tons.[29] Among the most widely used polymers, polyvinyl chloride (PVC) is worst in terms of its constituent monomer and common additives, including benzene, phthalates and lead stabilizers.[330] A recent review concluded that there is inadequate research on the mechanisms of MP toxicity.[359]

- Controlled studies on humans are not permitted, but — in addition to toxicity — exposure to MPs causes a laundry list of negative impacts and stimulation of immune responses to human cells *in vitro* and to non-human animals *in vivo.*

- Studies have shown that exposure to MPs induces an immune response as the body responds to the potentially harmful substances.[360]

- As one example, it has been shown that polystyrene particles are a potential immune stimulant. They trigger the emission of cellular defensive chemicals, cytokines and chemokines, a release that is proportional to the size and number of MPs.[361]

- Others have shown that microplastics made from PVC and ABS polymers can trigger an immune response in human cells.[362] High concentrations of MPs can provoke immune and stress responses and induce reproductive and developmental toxicity in model animal and cell culture experiments.[360]

As one example, it has been shown that polystyrene particles are a potential immune stimulant. They trigger the release of cellular defensive chemicals, known as cytokines and chemokines, that are proportional to the size and number of MPs.

Microplastics can cause toxicity through oxidative stress and inflammatory lesions, as well as metabolic disturbances, neuro-toxicity, and increased cancer risk in humans.

Autophagy is the body's way of cleaning out damaged cells.

Cytotoxity occurs when a substance damages cells in the body.

Oxidative stress can lead to cell and tissue damage.

- It has also been shown that MPs can cause toxicity through oxidative stress and inflammatory lesions, as well as metabolic disturbances, neurotoxicity, and increased cancer risk in humans.[329] It also appears that MPs can have a synergistic effect, making worse the toxic effects of BPA on human cells *in vitro*.[363]

- Various studies have reported changes in microbiota and digestive enzyme production in the digestive system, inflammatory processes in the respiratory system; circulatory and reproductive system disorders; and neurotoxicity, inducing behavioral changes.[364]

- Research also indicates that microplastics can cause lung and gut injury, and effects include oxidative stress, cell damage, inflammation, and impairment of energy allocation functions.[365]

- Apoptosis, the programmed death of cells, has been shown to be induced my MPs acting on both human and mouse brain cells.[366] Similarly, in rats, polystyrene (PS) microplastics can cause myocardium apoptosis triggered by oxidative stress as well as cardiovascular toxicity by inducing cardiac fibrosis.[367]

- Studies on human umbilical vein endothelial cells (lining of blood vessels) showed that polystyrene MPs inhibit tube-forming capacity, and cause autophagy and necrosis-mediated cytotoxicity in ways that are proportional to MP levels.[368]

- MPs made from polyethylene (PE) and PS have been shown to induce cytotoxicity due to oxidative stress for both cerebral (brain) and epithelial (surface lining) human cells.[369]

- Microplastics also appear to cause reproductive and even inter-generational harm as well. Negative impacts on male fertility have been studied in mice, and are suspected in humans.[370] Even inter-generational impacts of MPs have been documented, with metabolic disorders found in offspring of mice exposed to MPs.[371]

Carcinogenicity

- The possible carcinogenicity of MPs remains very poorly understood. Investigators have laid out a mechanistic pathway to MP carcinogenic potentials caused by reactive oxygen species, induction of oxidative stress, genome instability, and chronic inflammation.[372]

- However, the occurrence of these processes being triggered by microplastics, and subsequently leading to cancer, has not been studied in humans or other animals.

- Similarly, it has been pointed out that there are no studies that demonstrate a carcinogenic potential of polystyrene or polyvinyl chloride MPs, even though the corresponding polystyrene (PS) and PVC monomers (styrene and vinyl chloride) have been classified by the International Agency for Research on Cancer (IARC) as potentially carcinogenic substances (carcinogenicity classes B2 and 1, respectively).[323, 373]

Microplastics also appear to cause reproductive and even inter-generational harm as well. Negative impacts on male fertility have been studied in mice, and are suspected in humans.

Special concern has been expressed about the possibility of microplastic-related cancer risks in children. A possible connection between BPA exposure and breast and prostate cancer is well known.

- It is concerning that microplastics abundantly adsorb a number of well-known carcinogenic compounds, like some polycyclic aromatic hydrocarbons (PAHs), which can be transferred to seafood items that can then cause an elevated cancer risk.[374]

- In addition to adsorbed contaminants, intentional plastic additives like bisphenol-A (BPA) and phthalates in MPs are known to trigger immune responses potentially linked to development of diseases including cancer. Special concern has been expressed about the possibility of MP-related cancer risks in children.[183] A possible connection between BPA exposure and breast and prostate cancer[375] is well known.[376]

*Microplastics **adsorb** carcinogens. The cancer-causing polycyclic aromatic hydrocarbons (PAHs) stick to the MP surface and can be transferred to seafood items.*

Health Effects Caused by Inhalation and Ingestion of MPs

- Because the uptake pathways are through air, food, and water, the two organ systems that can be expected to be most directly affected by MPs are the *lungs*[333] and *digestive tract.* Compared to ingestion,

the inhalation pathway remains remarkably poorly studied,[377] especially compared to other air pollutants. Much of the research in this area comes from occupational studies, discussed later, where workers are exposed to MPs at elevated levels and for extended periods of time.[378]

One piece of good news is that wearing virtually any kind of breathing mask reduces the inhalation risks of MPs. Indeed, wearing an N95 mask reduces the inhalation risk of MPs by 25 times.

- Both MPs and nanoparticles (NPs) can be inhaled and reach the alveoli of the lungs, but it is believed that only NPs can penetrate into the bloodstream.[378] Lower density, smaller particles, e.g., polyethylene (PE) are better able to reach deep airways,[379] although fibers as large as 250 µm have been found in the deep lung.[380]

- A detailed study on both normal and asthmatic mice, found a wide variety of detrimental effects, raising urgent concerns for actions to reduce MPs in air.[381]

- Similarly, an inhalation study on rats with polystyrene MPs at the low end of the size range caused alterations in several markers related to physiological, serum biochemical, hematological, and respiratory function, though not at the organismal level for the conditions tested (up to 14 days exposure).[382]

- One piece of good news is that wearing virtually any kind of breathing mask reduces the inhalation risks of MPs. Indeed, wearing an N95 mask reduces the inhalation risk of MPs by 25 times.[383]

- Considerably more is known about the effects of MPs on the digestive tract and the gut biota, whose importance to several dimensions of human health has become widely recognized.[384-386]

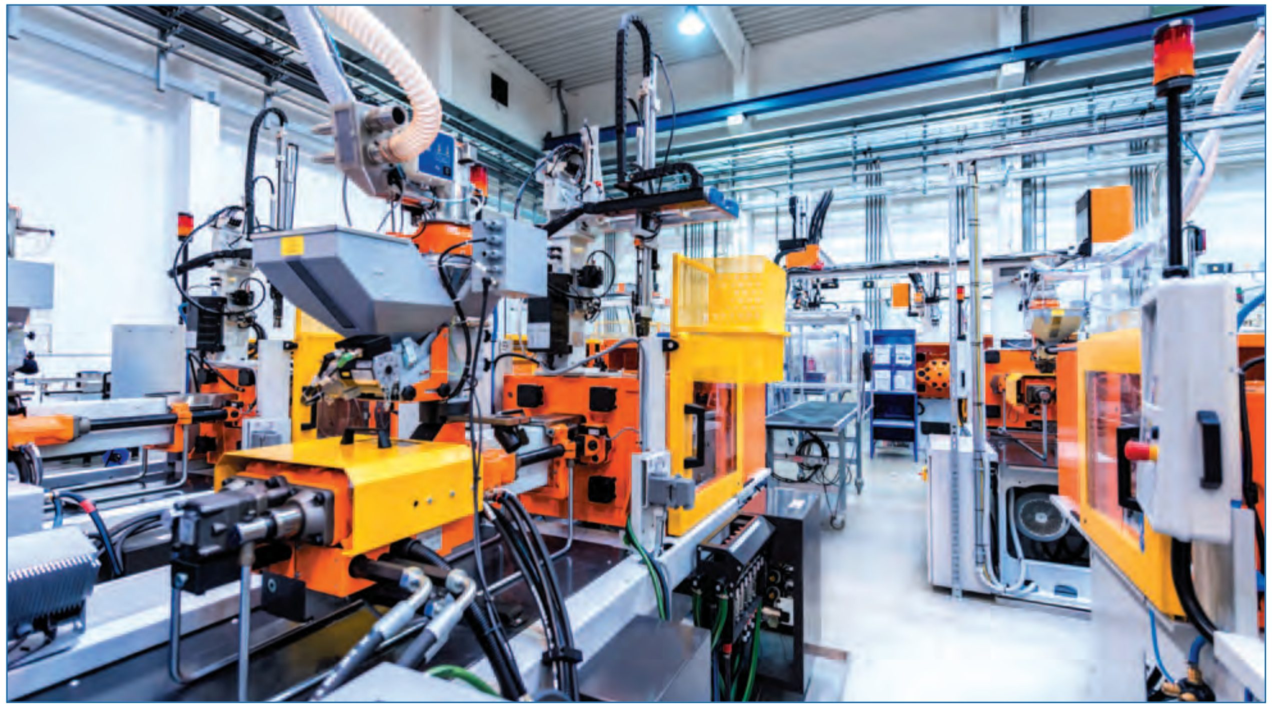
- From numerous animal studies it has been shown that exposure to MPs leads to impairments in oxidative and inflammatory intestinal balance, disruption of the gut's epithelial permeability, and immune cell toxicity.

In one of a few long-term exposure studies (up to 48 days), human intestinal cells were exposed to small polystyrene MPs. Cytotoxicity and cell mortality were observed in as little as 24 hours.

Cytotoxicity = the amount of damage to a cell caused by a substance like plastic.

Cell mortality = the death of cells

- Together, these negative effects may promote the development of chronic immune disorders.[387] Dysbiosis is the disruption of the symbiosis between host and the natural gut microbiota community.
- MPs can foster dysbiosis by introducing foreign and potentially pathogenic bacteria, as well as chemicals within the particles or adhering to them. Dysbiosis may interfere with the host's immune system and trigger the onset of chronic diseases, and promote pathogenic infections.[388]
- MPs can have negative impacts on the essential gut microbiota and gut cells directly, so it is not necessary for MPs to pass across the gut wall for there to be a negative human health effect.[389] As usual with negative human health impacts, many conclusions must rely on animal research, *in vitro* studies on human cells, and modeling based on detailed understanding of human physiology and biochemistry.
- Studies have shown that MPs can cause oxidative damage and inflammation in the gut, destruction of the gut epithelium, reduction of the mucus layer, microbial disorders, and immune cell toxicity.[390]
- *In vitro* studies on human cells showed that PS, PET, PE, and PVC microplastics all caused numerous health problems including reduced lipid digestion.[391] A similar disturbance of energy and lipid metabolism was measured directly in mice.[349] The same study revealed oxidative stress and changes in several biomarkers, indicating potential toxicity from exposure to MPs.
- In one of a few long-term exposure studies (up to 48 days), human intestinal cells were exposed to small polystyrene MPs. Cytotoxicity and cell mortality were observed in as little as 24 hours.[392] Generation of Reactive Oxygen Species (ROS, one indication of immune response to cellular distress) was also documented. The investigators concluded MPs could cause intestinal disorders with lower levels of plastics but over longer exposure times.



Workers in plastics industries are known to develop many kinds of cancer because of chronic exposure to high levels of airborne microplastics.

Occupational risks research

- Some studies examine damaging health effects in workers exposed to MPs at high levels and/or extended periods of time. It may be difficult to extrapolate down to conditions experienced by the majority of the population, but insights into possible mechanisms and outcomes can be obtained directly for humans.
- Workers in plastics industries are known to develop many kinds of cancer because of chronic exposure to high levels of airborne microplastics.[393] Workers in textile plants are exposed to high levels of fibrous MPs. Inhalation of synthetic fibers has been linked to respiratory lesions and chronic bronchitis.[394]
- Flock workers are exposed to small fibers that are glued to a surface to achieve a desired texture. One study on nylon flock workers found eye and throat irritation, respiratory symptoms, and generalized aches and fevers.[395]

- It is also known that PVC workers undergo persistent inflammatory stimulation, which can cause pulmonary fibrosis or even carcinogenesis.[378]

PVC workers are exposed to VC and PVC dust, which has been linked to undifferentiated restrictive lung disease, and to toxicity caused by the dust or its thermal decomposition products.

- PVC and its monomer, vinyl chloride (VC), are both known to be intrinsically hazardous even without additional chemical additives or adsorbates. Still, PVC particles containing additives produced a higher inflammatory potential than that triggered by additive-free PVC particles.[396]

- PVC workers are exposed to VC and PVC dust, which has been linked to undifferentiated restrictive lung disease, and to toxicity caused by the dust or its thermal decomposition products.[397] A worker who was exposed to thermoplastic PVC dust for 10 years was shown to have lung lesions and macrophages (specialized cells whose function is to destroy harmful invading organisms) surrounding PVC particles.[398]

- This study concluded that PVC dust may cause pneumoconiosis and secondary systemic sclerosis. Supporting these results, when PVC dust was administered to rat lungs in a single dose, numerous biochemical markers were triggered for up to 150 days, and inflammation and lesions developed.[399]

Data/research limitation

- Nearly every one of the copious studies on MPs and human health concludes with a caution about important information gaps and with a plea for more research to fill them.

- Some information gaps come from challenges in conducting human research in ethical ways. Another obstacle is that very high levels of MPs must sometimes be used to generate effects that might otherwise be caused by lower amounts over much longer (e.g., lifetime) exposures. Furthermore, comparison between studies is complicated by inadequate methods of separation and analysis[400] and lack of

universally recognized standard techniques.[401] One frequently cited issue is the need to better understand MPs at the small end of the size range. This is critical because numbers increase dramatically with decreasing size.

- Smaller particles are likely to be more hazardous (e.g., more likely to translocate in the body). They are the most difficult to measure,[402, 403] and so are often missed.

- A recent article in *Science* magazine bemoaned the lack of crucial data on exposure and hazard that mitigated against successful risk assessment for MPs and humans.[404] Indeed, it has been pointed out that so far there are no completed risk assessments for microplastics on human health.[405]

- Furthermore, it has been argued that because of knowledge gaps and inconsistent methodologies, assessment of risk is currently not even feasible.[406] The following quote is a typical judgment:

A recent article in Science magazine bemoaned the lack of crucial data on exposure and hazard that mitigated against successful risk assessment for MPs and humans. Indeed, it has been pointed out that so far there are no completed risk assessments for microplastics on human health.

"Where is the evidence that human exposure to microplastics is safe?" The authors remind readers of the oft forgotten adage that "absence of evidence is not evidence of absence."

"Scientific results aimed at establishing a possible health risk for contaminants associated with microplastics are rather controversial. The risk assessment of microplastics in foodstuff is still at a very early stage and very few studies on the monitoring of microplastics in foodstuff and their effects on human health are available. Additionally, it is difficult to compare results from different studies as methodologies and study designs are not uniform."[407]

- The World Health Organization produced a report in 2019 (Microplastics in Drinking-Water) that concluded there is "no evidence to indicate a human health concern."

- But this assertion was strongly refuted in an article entitled, "Where is the evidence that human exposure to microplastics is safe?" The authors remind readers of the oft forgotten adage that "absence of evidence is not evidence of absence."[408] Clearly there is a need for further research to provide important evidence on this potentially hazardous new pollution class.

11. Reducing Plastic Pollution

- Plastic waste and microplastics are a big problem that demands multiple management strategies. Some of these have already begun to be implemented, while others exist mainly as suggestions for future implementation.

- Plastic reduction strategies range from regulation of production and consumption, green design, recycling, reducing use, extended producer responsibility (EPR), to improvements in waste collection systems, and use of bio-based and biodegradable plastics.[409] Other strategies can include a reduction in packaging, education, and beach cleanups.[410]

- Plastic management should begin with an understanding of the scale and the seriousness of the problem. Over the past 70 years, roughly seven billion MT of plastic waste was generated, of which only about 9% has been recycled, and 12% incinerated, with the remaining 79% either landfilled or released into the environment.[105]

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Plastics entering the ocean as litter are supplemented by lesser but significant amounts of tire wear particles (TWPs) and fibers from textiles.

- Mismanagement of waste is probably the single biggest problem, with just five countries responsible for 56% of global plastic waste: China, Indonesia, Philippines, Vietnam and Sri Lanka.[411]

- Plastics entering the ocean as litter are supplemented by lesser but significant amounts of tire wear particles (TWPs) and fibers from textiles.[105]

Inaction

- Despite the enormous quantity of plastics released into the environment, and the ubiquity of MPs in every corner of nature, some have argued that the problem is minimal, at least from a human health standpoint.[412]

- One analysis suggested that microplastics from food and beverages probably constitute only a minor exposure pathway for plastic particles and associated chemicals to humans, and that exposure to other plastics in our everyday lives is greater.[413] Also, the World

Health Organization's 2019 report (Microplastics in Drinking-Water) concluded there is "no evidence to indicate a human health concern."

- But others refute this minimization, both because the level of our current uncertainty[414] and the complexity of the plastics cycle,[415] which so far make a true risk assessment impossible.[406]

- In addition, inaction will probably lead to ever greater levels of MPs in air, water, and in soils, as plastics degrade slowly. Furthermore, there are additional environmental harms posed by plastic waste, including entanglement of wildlife and their ingestion of both macro- and microplastics,[416, 417] and squandering of resources used to produce throwaway plastics.[415]

- Finally there is an unwillingness by many to be forced to ingest and breathe MPs daily, whether harm can be demonstrated or not.[415, 418, 419]

There are additional environmental harms posed by plastic waste, including entanglement of wildlife and their ingestion of both macro- and microplastics, and squandering of resources used to produce throwaway plastics.

Natural Degradation

- If allowed to enter and remain in the environment, what happens to plastics over time? It is often suggested that plastics persist in the environment for up to 1000 years, though this will depend on the polymer, the physical nature of the plastic item, and the environment in which it is found.

- But some studies find relatively short lifetimes for certain plastic articles, like 58 years for some plastic bottles.[230] Several studies suggest that plastics can be degraded, albeit slowly, by several classes of bacteria and fungi[420-422] and that plastics in sewage effluent may even have unusual assemblages that favor degradation.[22]

- Perhaps this natural degradation can help to explain some of the "missing plastic," the 99% of the 150 MT believed to have been added to the ocean but not measured to be there today.[105]

***Macroplastics** are plastic items larger than 5 mm — or slightly larger than 3/16 of an inch.*

- Natural degradation is a management strategy that deserves much greater research to understand its nature and quantify its magnitude.

Many polymers are not recyclable in an economically feasible way, and most if not all plastic types can be recycled only a couple of times before they become chemically degraded.

Recycling Plastics

- Recycling plastics was once viewed as the best solution to the waste problem,[25] but it has largely come to be judged as a failure. Optimistic predictions from a decade ago[423] have not been borne out and only a small fraction of plastics will ever be recycled.

- This occurs only partly through a failure of the collection system, but also because the market for recycled materials has collapsed.

- Many polymers are not recyclable in an economically feasible way, and most if not all plastic types can be recycled only a couple of times before they become chemically degraded.

- The estimate of 9% of plastics being recycled by the U.S. is inflated, because more than half of this amount was sent overseas to countries with poor ability to manage waste. Much of this plastic is burned or dumped into rivers, explaining the high proportion of pollution issuing from a few countries.

- Investigative journalists have also shown that plastics recycling in the U.S. was a successful effort by industry to mislead the public and make them believe falsely that plastics could and would be reprocessed and reused. In 2020, National Public Radio (NPR) reported on plastics recycling in a story titled, *How Big Oil Misled The Public Into Believing Plastic Would Be Recycled.*

- The very symbol of recycling (three arrows in a circle labeled reduce, reuse, recycle) was an industry marketing invention rather than a consumer guide, as is often believed. The consequence of the combination of all these factors is that less than 10% of global plastics are ever recycled.[424]

- Plastics recycling seems unlikely to be a major part of the solution to plastics waste in the future. In fact, by giving people a false sense of "doing their part," it may cause them to take fewer measures that might reduce generation of plastic waste or actually benefit the environment in other ways.

A circular economy is "an economic system that targets zero waste and pollution throughout materials lifecycles, from environment extraction to industrial transformation, and to final consumers… Upon its lifetime end, materials return to either an industrial process or… safely back to the environment as in a natural regenerating cycle…"

Circular Economy (CE)/Extended Producer Responsibility (EPR)

- The Circular Economy (CE) is a concept that is gaining considerableattention as an approach to deal with many environmental problems stemming from industrial materials.

- A circular economy is "an economic system that targets zero waste and pollution throughout materials lifecycles, from environment extraction to industrial transformation, and to final consumers… Upon its lifetime end, materials return to either an industrial process or… safely back to the environment as in a natural regenerating cycle…"[425]

A linear economy is often defined as raw materials that are collected, then transformed into products that are used, and then discarded as waste.

- The existing wasteful alternative is often called a Linear Economy. A linear economy is often defined as raw materials that are collected, then transformed into products that are used, and then discarded as waste.

- Extended Producer Responsibility (EPR) is one tool to achieve a circular economy by holding producers responsible for the costs of managing their products at the end of their useful lives.

- Many have called for development of CE and application of EPR to mitigate the plastic waste problem.[426-429] It has been suggested that plastic pollution is the inevitable result of an inherently wasteful linear plastic economy, whose cost has been estimated at more than $2.2 trillion per year.[430]

- These investigators call for an industry-led initiative to produce future fossil fuel-derived plastics by techniques that promote CE, methods they see as key to stemming plastic waste flows. These approaches include making used plastic a cashable commodity, incentivizing recovery, and accelerating implementation of polymer-to-polymer reuse technologies.

- CE as a way to minimize plastics pollution is being considered at vast scales. The European Union (the second-largest world economy in terms of GDP) has developed a plan to move in that direction. Their approach to achieve CE to solve the plastics problem has been described in detail in the report "A European Strategy for Plastics in a Circular Economy (2018)."[431-433]

Source reduction

- There are no plans or even viable methods to remove microplastics once they are in the environment. Most microplastics come from the fragmentation of macroplastics, and recycling measures are failing, so actions to reduce plastic litter are one of the best ways to ameliorate the MP pollution problem. Reducing the total amount of plastics generated, used, and discarded lessens the need for all other strategies.

- Many have called for source reduction[429, 434, 435] as a primary strategy to reduce plastics pollution. At the same time, some analysts suggest that plastics can sometimes have a smaller carbon and energy footprint than alternative materials, but such analyses are sensitive to uncertainties introduced by factors like unknown reuse and eventual disposal methods.[436, 437]

- Furthermore, such single-dimensional analyses generally neglect competing environmental harms like health impacts to humans, animals, and ecosystems. Still, plastics do possess many desirable characteristics, and source reduction would require replacing them with viable alternatives. Nevertheless, we all managed without plastics before 1950, so living in a low-plastic world is not an unrealistic possibility.

Many have called for source reduction as a primary strategy to reduce plastics pollution.

Unfortunately, even reducing or eliminating sources may not be enough, because an enormous quantity of plastic has already been released and may persist in the environment for hundreds of years.

- Once again the EU may provide a model for ways to reduce reliance on plastics and consequent generation of waste. Europe is using a multipronged strategy that includes product bans, EPR laws, taxes and fees, and ecolabeling.[438] (Ecolabeling is a way of certifying a low level of environmental harm, like toxicity, for specific product categories.)

- These researchers provided recommendations about which of the EU's strategies would be most effective in moving the U.S. away from its overreliance on recycling and disposal, and toward reduction of the amount of plastic waste generated. They concluded that outright bans of specific single use products were most effective, and ecolabeling least.

- Unfortunately, even reducing or eliminating sources may not be enough, because an enormous quantity of plastic has already been released and may persist in the environment for hundreds of years.

- In this way, plastics are similar to CO_2, which has been allowed to build up and is expected to persist for up to 1000 years. This conundrum was recognized long ago,[439] but 30 years have gone by with very little action.

- Perhaps a successful model for plastics source reduction already exists in the Montreal Protocol, which was rapidly developed to deal with chemicals (CFCs) that were known to deplete the earth's protective stratospheric ozone layer. Discovery of this problem was awarded the 1995 Nobel Prize in Chemistry.

- Forty-six countries signed the Protocol and quickly restricted their use and inevitable release of CFCs. In a similar fashion, it might be possible to develop a global compact to reduce the production of virgin material within the plastics industry by regulating both the polymers and chemical additives as controlled substances.[440]

- Finally, treaties to limit release of greenhouse gases (GHGs) might also be used to reduce sources of plastics. Production of plastics generates GHGs, and plastics eventually break down to CO_2 or even stronger heat-trapping gases, like methane,[441] and plastic production accounts for about 10% of all fossil fuels. Thus, efforts to limit climate change might be leveraged to also lower plastics production.[442]

Biodegradable Plastics and Bioplastics

- Another strategy is to engineer less harmful plastics. This can include using biological sources rather than fossil fuels to synthesize so-called bioplastics, or designing them to biodegrade more rapidly in case they are released to the environment.[409, 443]

- **Bioplastics** can be created from materials such as plant oils, corn starch, or wood chips, often via the intermediary of bioethanol (alcohol produced from biological source materials).

- While they are generally considered to be less harmful than fossil fuel-based alternatives, bioplastics do have environmental impacts, including land used to produce the biomaterials, and GHGs released during their production.[444] There is also the ethical issue of diverting potential edible crops (like corn) to industrial uses, which can increase food insecurity in vulnerable populations.[445]

- **Biodegradable plastics** are designed to be more easily broken down by microbes in the natural environment than are conventional types. These polymers deserve considerable more study, but so far there remains uncertainty about the extent to which they degrade under natural conditions (soils, sediments, waters).[446]

- For example, there is evidence that many ordinarily biodegradable polymers do so much more slowly in seawater.[447] Furthermore, there is a risk that more rapid degradation of macroplastic simply creates MPs more rapidly.[105, 448]

Bioplastics can be created from materials such as plant oils, corn starch, or wood chips, often via the intermediary of bioethanol.

Single use plastic (SUP) shopping bags are another product that is increasingly being banned. Prohibitions exist at locations on all continents, and more than 300 U.S. cities limit their use.

- It is worth noting that biodegradable plastics can be synthesized from fossil fuels, and bioplastics can be formed as polymers that are not biodegradable. The best case would be to use biological feedstocks to produce plastics that have an enhanced ability to biodegrade.

- While both bioplastics and biodegradable plastics show promise, so far they represent only about a percent of global plastics production in combination.

Bans and Fees

- Outright bans on certain products can be very effective, even if they may also be difficult politically to implement. However, in the world of plastics pollution, successful models for bans already exist.

- As one example, as early as 1989, dumping of plastics into the sea was prohibited globally by Annex V of the International Convention for the Prevention of Pollution from Ships (MARPOL). Nevertheless, it was recently discovered that significant amounts of marine plastics must still be coming from ships.

- Investigators have found "young" Asian plastics (especially bottles) in the central southern Atlantic, litter that computer models showed could not have floated from Asia.[449] The plastic litter must therefore have come from marine sources such as ships.

- Microbeads, which are used mainly in cosmetics, have also been successfully banned at a broad scale, starting in 2014.[57] There are more than a dozen countries, including the United States, that currently have bans, and the number is growing.

- Single use plastic (SUP) shopping bags are another product that is increasingly being banned. Prohibitions exist at locations on all continents,[450] and more than 300 U.S. cities limit their use.[451] Outright bans are more common than the alternative, charging a small fee for the bags.[450]

Bans on plastic items may be effective, but they are not a panacea. One question is what is used to replace the plastic items.

- Economic incentives, a sort of negative fee, can also be a way to increase recycling and reduce plastic waste. When plastic bottles have a redemption value (true in just 10 states so far), beach litter is about 40% lower.[452]

- There is also an environmental justice component, as the reduction in beverage containers with deposit value was greater in areas with low socioeconomic status, where total litter loads are highest. This is compelling evidence that bottle deposits reduce plastic litter.[452]

- Bans on plastic items may be effective, but they are not a panacea. One question is what is used to replace the plastic items. A study in Australia found that the total amount of all waste, including non-plastics, declined only slightly when SUP bags were banned as people switched to disposable non-plastic alternatives.[453]

- Nevertheless, support for the ban grew over the seven-year period of study, which is not always the case. Sometimes there is resistance

Children seem especially well-suited to educational interventions because youth are frequently an important source of social influence among their peers, parents, and community.

to SUP bag regulations, as well as uncertainty in measuring the effects, and undesired side-effects like substituting alternatives with their own environmental impacts (e.g., greater carbon footprint).[450]

- Still, bans and levies remain a valuable option, with between 33 and 96% effectiveness in reducing bag use.[454]

Education

- Controlling pollution at its source is more effective and cost efficient than end of pipe solutions.[455, 456] For plastic waste, this partly means educating consumers to use alternatives to plastic and to avoid littering or other individual mismanagement behaviors.
- Yet proper disposal still generally means more plastic redirected to landfilling or incineration, so its utility may be limited
- Education is often encouraged as a way to reduce plastics pollution[57, 410, 457-459] and littering generally, though evidence of its effectiveness is mixed.[460] In one study, self-reporting by British school- children indicated that an educational program augmented awareness of marine litter and increased engagement in actions to reduce its potential causes.[461]
- Children seem especially well-suited to educational interventions because youth are frequently an important source of social influence among their peers, parents, and community.[462]
- Citizen Science is another way to involve and educate the public in the harms from plastics pollution and ways to minimize them.[463] Education about plastics pollution seems especially important, considering the public's unfamiliarity with the problem, and that learning is probably key to changing human behavior.[464]
- In surveys conducted in Shanghai[419] and Chile[465] only 26% and 27% of respondents were aware of microplastics before polling. Relative risks are also poorly understood.
- The environmental impact of paper, cardboard,and metal are rated by consumers in accordance with scientific understanding, whereas plastic packaging is underestimated and glass and biodegradable plastic packaging are highly overestimated.[466]
- In the end, the utility of education to reduce plastics pollution is complicated by the extreme complexity and variability of human attitudes and values about the environment and its intersection with their daily lives.
- People value plastic's desirable characteristics and use it routinely for numerous purposes even in the face of substantial known environmental harms.[467] Education, including experiential learning like Citizen Science,[468, 469] can help to overcome habits and norms to reduce plastic use and subsequent pollution, though long-term effects may be uncertain.[467]

People value plastic's desirable characteristics and use it routinely for numerous purposes even in the face of substantial known environmental harms.

Clean Up

Macroplastics are a major portion of anthropogenic litter and persist in the environment longer than almost all other categories. Anthropogenic litter can be trapped and removed from point sources like storm drains before entering the natural environment.

- The last resort in reducing plastics pollution is to remove it directly from the environment. For MPs, there are no practical removal processes,[419] though a number of different techniques can help to reduce levels in wastewater.[470]

- It has also been shown that seagrass beds produce hydraulic conditions that are especially good at removing MPs,[471] and thereby provide an important ecosystem service.[156, 472]

- Macroplastics are a major portion of anthropogenic litter and persist in the environment longer than almost all other categories. Anthropogenic litter can be trapped and removed from point sources like storm drains[473] before entering the natural environment.

- Once distributed throughout aquatic ecosystems, macroplastics may become concentrated in natural traps like mangrove forests[474-476] and salt marshes and coral reefs[477] though removing them from these systems is complicated.

- Beach clean ups are probably the most widely practiced method of removing plastics from the environment, and have been carried out globally, for example in Turkey,[478] India,[479] Spain,[480] Malawi,[481] China,[482] Greece,[483] Nigeria,[484] and Canada.[485]

- However, such activities probably only resolve a very local problem.[486] Furthermore, while they may increase participants' awareness,[478, 483, 484] clean ups also reduce litter's visibility, so they may diminish the broader public's consciousness of the problem.

12. Conclusion

> *Plastic is forever....Whether future archaeologists will find our plastics neatly arranged in dump sites or scattered everywhere across the globe, find them they will. They will still be there long after the wood has rotted, the concrete crumbled and the iron rusted away. This will be known as the Plastic Age.*
>
> — **Christine Duerr, 1980**

Plastics have become a global pollution problem of enormous magnitude. The quantity of plastics produced each year is similar to the weight of all humans on earth.

- Plastics have become a global pollution problem of enormous magnitude. The quantity of plastics produced each year is similar to the weight of all humans on earth.

- Plastics and their fragments are found everywhere, from the highest mountains to the deepest ocean trenches, from the Arctic to the Antarctic, and in all other places formerly thought of as pristine.

- Beginning with their first significant use by consumers in 1950, the quantity of plastics produced has grown annually with no indication of slowing.

It is expected that within 10 years, greenhouse gases released by production and disposal of plastics will exceed that from burning coal.

- About half of the plastic is used once, then discarded, continuing to exist for hundreds of years. A significant fraction of all extracted fossil fuels is used as feedstock to form plastics and as an energy source to manufacture them.
- It is expected that within 10 years, greenhouse gases released by production and disposal of plastics will exceed that from burning coal. There is evidence that the period of human dominance on earth will be evident in the geologic record as a layer loaded with plastics, an epoch coming to be called the Plasticene.
- Full sized plastic objects, like bottles and other containers, break down to smaller pieces called microplastics (MPs) and nanoplastics (NPs).
- MPs typically fall in a size range similar to the diameter of a human hair or the thickness of a piece of paper, but they encompass a range from about the size of a grain of rice down to the smallest particles captured on filter paper, about 100 times smaller than the limit of human vision.
- NPs are smaller than that, and include particles the size of large molecules. A single small plastic water bottle could theoretically fragment into 20 trillion MPs (20,000,000,000,000) that are 1 micron (0.001 mm) in size. For the very smallest MPs (0.1 micron), the number is 20 quadrillion (20,000,000,000,000,000) for each bottle.
- Microplastics come from many sources, but especially plastic containers (bottles, food packaging), synthetic textile fibers, and tire wear particles.
- The entirety of the plastics cycle in the environment remains poorly understood, but MPs are found in essentially all oceans, beaches, estuaries, rivers, lakes, groundwaters, air, soils, animals,

plants, and all kinds of food and beverages. They are unavoidable. Your next meal and drink, your next breath, will all contain MPs.

Your next meal and drink, your next breath, will all contain MPs. People take up MPs in large quantities by ingesting ordinary foods and beverages and through inhaling indoor and outdoor air.

- People take up MPs in large quantities by ingesting ordinary foods and beverages and through inhaling indoor and outdoor air. Many impacts on living things have been demonstrated via studies of animals and on human cells in laboratory experiments.
- Evidence is overwhelming that biological impacts can be substantial under these conditions. Lacking are long-term studies at real world concentrations, and these are urgently needed to evaluate the true human health risk of this ubiquitous contaminant class.
- Plastics are composed of a diversity of different polymers to which have been added plasticizers and other potentially toxic chemicals to alter their properties. MPs risk damaging human health both because they contain and release these harmful additives, and because they adsorb and carry toxic substances.

Plastics also harm ecosystem health. Large pieces entangle and are ingested by a wide variety of animals, often leading to death. Furthermore, MPs are mistaken as food and cause numerous harms to the minute creatures that make up the base of global food webs.

In addition, potentially disease causing microbes live within the hospitable biofilm layer that tends to form on MP surfaces.

- Plastics also harm ecosystem health. Large pieces entangle and are ingested by a wide variety of animals, often leading to death. Furthermore, MPs are mistaken as food and cause numerous harms to the minute creatures that make up the base of global food webs.

- MPs contribute to global climate change by slow conversion to CO_2 and to even more potent methane, nitrous oxide, and ethylene, as well as other greenhouse gases. Additional heat trapping gases are released during production of plastics or by their disposal via incineration.

- Scientists are working furiously to better understand MPs and the hazard they pose. But numbers of particles increase dramatically as size decreases, and so does the difficulty of detecting and quantifying them. Consequently, our understanding of the nature and risk of MPs declines with these much more abundant smaller sizes.

- Nanoplastics, which are orders of magnitude more abundant than MPs, have yet to be even directly detected in nature because of these methodological limitations, yet their risk may well be much greater. Much more research — especially that which simulates real world levels and exposure times — is desperately needed.

- Almost all microplastics come from breakdown of macroplastics rather than direct production, so it is impossible to control the small particles without constraining plastic waste.

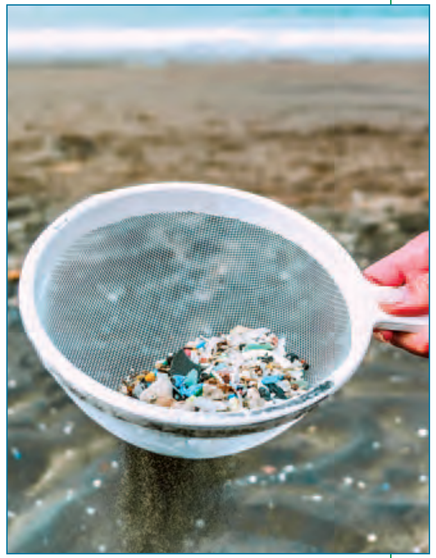
- Recycling is not working, and may give a false sense of success. Indeed illusory recycling, as currently practiced, was created by industry probably for that very purpose.

- There is no feasible way to remove the small particles once they are generated in the environment.

- Instead, we need to reduce their source, working at every level from individual to global, enlisting government, industry, researchers, and consumers, and using tools ranging from plastic substitutes, to legitimate recycling, to extended producer responsibility.

- But realistically, the single best solution is to drastically curtail the production and use of plastics that are used only once and then discarded. This constitutes the majority of plastic products currently manufactured.

- Given time, nature has incredible self-cleansing capabilities, even if it may take decades, but first the source of harm must be eliminated. Recommendations follow that explain ways that plastics can be reduced or even eliminated.



There is no feasible way to remove the small particles once they are generated in the environment.

13. Recommendations

The International Community

Plastic production and consequent waste is a global problem requiring international action. Microplastics (MPs) come almost entirely from degradation of macroplastics, so the control of MPs requires the reduction of plastic manufacturing and the reduction of plastic waste.

- Strengthen and enforce existing and proposed international treaties to reduce plastic production and disposal.
- More strongly administer MARPOL 73/78, the International Convention for the Prevention of Pollution from Ships, for example to reduce apparent releases of waste from Asian ships.
- Adopt and implement the five areas of recommendations of the G7 Oceans Plastic Charter and work to have others join to achieve the goal of zero plastic waste.
- Strongly support the proposed global treaty aimed at curbing plastic pollution, which will be discussed at the U.N. Environment Assembly in February 2022.
- Continue to conform to the Convention for the Protection of the Marine Environment of the North-East Atlantic (the 'OSPAR Convention') along with all of the contracting parties (Belgium, Denmark, the European Union, Finland, France, Germany, Iceland, Ireland, the Netherlands, Norway, Portugal, Spain, Sweden, and the UK). Work to establish similar regulations for the rest of the world's oceans.
- Encourage the European Commission's EU Plastics Strategy to reduce or eliminate intentionally added microplastics under its Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH) regulatory program.
- Incentivize improving global waste management to reduce plastics pollution by the worst waste generators, currently China, Indonesia, the Philippines, Vietnam, and Sri Lanka.

Recommendations for the Federal Government

Plastic production and plastic waste require federal action. Microplastics (MPs) come almost entirely from degradation of macroplastics, so the control of MPs requires the reduction of plastic production and its consequent waste.

- Ban future permits for new plastic manufacturing plants.
- Require Extended Producer Responsibility (EPR) for all plastics in order to shift the legal and financial responsibility to the manufacturers of plastics.
- Expand the Microbead-Free Waters Act of 2015 to ban manufactured microbeads in all consumer products, not just cosmetics and Over The Counter (OTC) pharmaceuticals.
- If genuine recycling becomes an important part of solving plastics pollution in the future, enact an approach like the European Commission's 2018 Europe-wide-plastics recycling plan. The European Commission has a set date of 2030 by which all plastic packaging must be recyclable. It also raises the extent of recycling to 55% of all packing material compared to the current European level of 30%. In the U.S., this rate is now less than 10%.
- Federal agencies like the National Science Foundation (NSF) and National Institutes of Health (NIH) should prioritize research on plastics and MPs and make special funding available to study them and their hazards.

Recommendations for State Governments

Plastic production and plastic waste require state action. Microplastics (MPs) come almost entirely from degradation of macroplastics, so the control of MPs requires the reduction of plastic manufacturing and the reduction of plastic waste.

- Ban any future permits for newly proposed plastic manufacturing plants.
- Require Extended Producer Responsibility (EPR) for all plastics in order to shift the legal and financial responsibility to the manufacturers of plastics.
- Ban plastic uses in all packaging, including for food and other products.
- Container redemption laws should be enacted in the 40 states that do not currently have them. Only ten states currently have container redemption laws. These are California, Connecticut, Hawaii, Iowa, Maine, Massachusetts, Michigan, New York, Oregon, and Vermont.
- Fund educational campaigns that will help make the public more aware of the importance of implementing the "Four Rs," which are "refuse, reduce, reuse, and recycle."

- Enact state laws, like the one in California that monitors the distribution and levels of plastics and microplastics in the environment. You cannot manage what you do not measure.
- Ban all remaining single use plastics that have not already been included in earlier state bans.
- Schools need to educate children about the importance of reducing the use of plastics. Children have a strong influence among their peers, parents, and community and can make a difference in reducing plastic uses.

Recommendations for Towns and Cities

- Ban any future permits for newly proposed plastic manufacturing plants.
- Ban as many single use plastics products as your town can pass.
- Test municipal drinking water for microplastics and retrofit treatment to eliminate them in drinking water.
- Recycle only those plastic products made from the two plastic polymers that are able to be successfully recycled: PET and HDPE (numbers 1 and 2). Ensure that they are actually recycled and not disposed as waste or exported.
- Do not collect plastic containers in categories 3–7, which are not recycled, but which give consumers the false belief that they are.
- Provide adequate numbers of street receptacles to prevent littering.
- Conduct street sweeping twice a month to help remove tire wear particles (TWPs) and macroplastics.
- Install hoods in all street catch basins to trap floatables, which are mainly plastics. Clean basins at least annually or whenever needed as they become full.
- Install end of pipe litter traps or other measures to capture plastics transported by runoff.
- Evaluate microplastics in treated sewage and upgrade treatment to reduce them.

Recommendations for Corporations

Corporations play a major role in causing plastics pollution and need to take a number of measures to help control the problem.

- Corporations that currently manufacture plastics must not create any new plastic manufacturing facilities and must reduce the amount of plastic from existing plants.
- Corporations need to support Extended Producer Responsibility (EPR) for all plastics that will shift the legal and financial responsibility to the manufacturers of plastics.
- Discontinue using plastic in the packaging of products. Many products are so heavily packaged in plastic that they require sharp tools to open them.
- Replace food storage and kitchen product lines with ones based on glass or other inert materials like stainless steel.
- Industry should avoid harming vulnerable infants with their plastic products. This should include making things like infants' feeding and water bottles from less harmful plastic resins and with lower amounts of additives, and using materials like shatterproof glass in place of plastic.
- Work to replace all conventional plastics with biodegradable and compostable plastics. Compostable plastics are broken down rapidly by microbes into nutrient-rich biomass, leaving behind no toxins or residue. Compostables are well-defined and governed by the U.S. Standard ASTM D6400-99, European Standard EN 13432, Canadian BNQ 9011-911/2007, and Japanese JBPA/2011.
- As industry moves to biodegradable and compostable plastics and other alternatives, it should use less hazardous polymers and include fewer additives.
- Industry should adopt a Circular Economy (CE) approach. This means incorporating used products as raw materials for making new ones. When manufacturing products, industry should Reuse-Repair-Refurbish-Remanufacture and then Repurpose.
- Produce plastics from biologically sourced raw materials, such as starch, cellulose, lignin and bioethanol. Use of these so-called bioplastics, which amount to about 1% of the current market, will reduce the dependence on fossil fuels, even if they will not reduce plastic waste.

- Industry is encouraged to work together in groups like the Alliance to End Plastic Waste (AEPW), which pledges to invest up to 1.5 billion dollars over the next five years on projects to keep plastic trash out of the ocean. The AEPW is an industry-funded, NGO, and non-profit organization composed of 28 companies. Founding members include BASF, Chevron Phillips Chemical, ExxonMobil, Dow Chemical, Mitsubishi Chemical Holdings, Proctor & Gamble, and Shell. Any such enterprise will need to be closely monitored by outsiders to ensure it is not simply a vehicle for greenwashing the members' public images.

Recommendations for Individuals

Individuals can help solve this problem by using less plastic whenever possible.

- Practice the Four Rs concepts: refuse, reduce, reuse, and recycle.
- Choose reusable products over single use ones.
- Select alternative materials to plastics, like glass, especially for storing food and microwaving.
- Reuse, recycle, and repurpose plastics at the end of their normal useful life.
- Encourage others to use the Four Rs through your social networks.
- Bring small reusable mesh bags to the grocery to hold produce.
- Buy bulk foods and put them in your own reusable containers.
- Choose products packaged in non-plastic containers, from eggs to milk to dishwasher detergent.
- Do not line trash cans or wastepaper baskets with plastic bags.
- Keep a reusable metal or glass water bottle – not plastic.
- Opening and closing plastic water bottles multiple times generates MPs that you will later ingest. Therefore avoid opening and closing plastic beverage bottles.
- Avoid polyester fleece fabrics, which release the greatest amounts of fiber MPs. Instead, use natural fiber fabrics or blends.

- Consumers can reduce MP fiber release from laundry by avoiding high water-volume washes, transitioning to appliances that use a lower water-volume, and ensuring that full wash loads are used. A device called the Lint LUV-R captures nearly 90% of microfibers from the wash.
- Consider keeping a plastics diary. Once a year, weigh all the plastics you discard during one week. Strive to waste less the next year.
- Never use products that contain manufactured microbeads.
- Pick up plastic litter. A single bottle has the potential to break down into more than a trillion MPs.

Recommendations for Future Research

There remain many unanswered questions about MPs and how they may harm human health. These should be immediate priorities for the research community.

- Increase research on small MPs (<100 microns). These are the most abundant and most likely to harm people and other animals.
- Study MPs that have been naturally or artificially aged. These are likely to carry more toxic substances and pathogens than are virgin particles.
- Establish standard protocols for sample collection, treatment, and analysis so that results of different investigators can be fairly intercompared. The National Academies of Science (NAS) should convene a committee to generate a report providing guidance on this topic.
- Investigators need to adopt clean techniques (filtered air laboratories and the like) to avoid sample contamination and erroneous results.
- Researchers need to guard against self-contamination of their samples with plastic additives that are almost ubiquitous in the human environment.
- Government, industrial, and academic researchers should monitor MPs in foods, beverages, and various environmental compartments (air, water, soils) with a view to their impact on human health.
- Researchers should close knowledge gaps that are impediments to conducting reliable risk assessments on human exposure to MPs, intake and translocation of smaller MPs and nanoplastics, chemical and microbiological hazards, and human health impacts.

- Research is needed on identifying the presence of microplastics in the human body in various tissues and organs.
- Scientists need to expand the range of organisms studied to allow greater generality of research findings.
- More investigations are needed with real world (lower) levels and long exposure times, rather than high-level exposure for short periods, as is commonly done at present. This shift in approach will require increased research funding by federal agencies.
- Additional study is needed to evaluate the health risk to vulnerable populations, like children and the immunocompromised.
- More research is needed on technologies to reduce plastic and MP pollution, especially safe substitutes for conventional plastics (biodegradable and compostable forms).
- We also need a better understanding of the fate and lifetime of plastics in the environment and where they wind up.
- Scientists can also contribute to strategies to achieve a more sustainable, circular economy, where materials normally considered waste by one industry can be repurposed as raw materials in another.

We recommended that all stakeholders from science, policy, and industry, to governments and individuals all work together. It will require action at all levels and by every sector to solve the global problem of plastics pollution and its impacts on human and ecosystem health.

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