Plastic Contamination of the Environment: Sources, Fate, Effects, and Solutions

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About This Report

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I. INTRODUCTION

A chemistry major and son of a chemist, Captain Charles Moore galvanized the movement to address plastic contamination. In 1997, while sailing home to Los Angeles from Honolulu, Hawaii, after a sailboat race, Moore and his crew motored through the doldrums in the North Pacific Subtropical Gyre and discovered the "North Pacific Garbage Patch." "I could stand on deck for five minutes seeing nothing but the detritus of civilization in the remotest part of the great Pacific Ocean," he says on his website.[1] The encounter grabbed headlines, triggered public concern, and inspired a host of scientific studies. Since then, scientists have documented garbage patches in every major open ocean,[2] and they project that plastics in the ocean will outweigh fish, pound for pound, by 2050.[3] This world would be unrecognizable to the chemist who started it all more than 100 years ago.

A Plastic Primer

When Leo Baekeland invented the first fully synthetic, commercially important plastic in 1907, little did he know that his creation would become the most widely used man-made substance. He made Bakelite by mixing phenol with formaldehyde under heat and pressure. His new "plastic"—a term he coined from *plastikos*, the Greek word for moldable—was soon used in cars, radios, and even jewelry.[4]

Plastic production exploded after World War II to generate a wide variety of polymers, from flexible to rigid and transparent to colored. The most popular plastics are polypropylene (PP), used in food containers, and polyethylene (PE). High-density polyethylene (HDPE) is the familiar component used for milk jugs, whereas low-density polyethylene (LDPE) is the flexible material of plastic bags. The construction industry makes pipes from polyvinyl chloride (PVC), and the textile industry crafts fabrics such as polyester from polyethylene terephthalate (PET). Polystyrene (PS) goes into drinking cups and rigid foam packaging. Together, these materials comprise nearly 80% of the plastic found in U.S. trash.[5]

Trashing the Planet and Economy

Disposal after a single use is the destiny of the majority of the 380 million tons of plastic produced each year.[6] Because the material is so durable, the bags, straws, soda bottles, food containers, and cups tossed out into landfills and the environment could linger for hundreds to thousands of years.[7] Flushed out to the ocean, the trash endangers marine life, such as sea turtles and birds, that mistake the floating bits for food, while plastic bags and fishing gear entangle seals and whales.

On land, as well as in lakes and oceans, plastic eventually breaks down into microscopic bits that can enter food webs. These microplastics are also manufactured intentionally in the form of polyethylene scrubbing beads for personal care products. Reporting for *Chemical & Engineering News* (*C&EN*), Cheryl Hogue writes, "After washing with these cleansers, consumers rinse the soapy stuff—along with its teeny spheres—down the drain, giving nary a thought to what happens to the plastic bits, which are less than 1 mm in diameter. Now, researchers are finding plastic microbeads in the Great Lakes. They say the miniscule spheres could harm aquatic animals that mistake them for food. Perhaps more ominously, they worry that the plastic balls could help transfer toxic pollutants from the Great Lakes to the food chain, including fish that people eat."[8]

Researchers are increasingly worried that fibers from fleece and other synthetic garments are making their way in to the environment, potentially damaging wildlife and ending up in our food supply, writes Melody M. Bomgardner for *C&EN*. "Scientists have dubbed these escapees 'microfibers' because they are commonly only tens of microns wide and millimeters long. They are a tiny, often invisible, subset of the larger class of microplastics." Bombardner spoke to Chelsea Rochman at the University of Toronto, who said, "When we look for them, microfibers are the most common type of microplastics we see in animals and sediments."[9] Bomgardner further writes, "Rochman says there is no doubt we are consuming microfibers when we eat certain type of fish—particularly those that are eaten whole like sardines or oysters. 'The big question is: Does it matter?' she asks. 'We can make estimates of how much microplastics we eat in a year but we don't know if there is cause for concern for human health.'"

Because plastics draw on fossil feedstocks, throwing them out after a single use is a waste of petroleum and money. A recent report from the World Economic Forum says "an overwhelming 72% of plastic packaging is not recovered at all: 40% is landfilled, and 32% leaks out of the collection system—that is, either it is not collected at all, or it is collected but then illegally dumped or mismanaged." As a result, the report concludes that 95% of plastic packaging material value—estimated at $80–120 billion annually—is lost to the economy after a short first use.[10]

A Persistent Pollutant

Plastic waste now penetrates every corner of the planet. Recently, a team of German researchers found microplastic contaminating organic compost destined for farmland. The compost, made from municipal green bin waste, contained up to 900 particles per kilogram.[11] A new study reveals that Arctic sea ice contains up to 12,000 microscopic particles per liter of ice.[12]

The world's accumulating plastic contamination demands a radical rethink of the plastic sector with a goal of zero plastic waste, says Boris Worm of Dalhousie University in a recent study. He calls for a global convention on plastic pollution that would reduce demand, capture litter, improve recycling, and provide incentives for the shift to a fully circular economy. Chemists and engineers have an essential role to play in the new plastic economy to ensure that plastic additives are safe, to redesign products and materials for more efficient recycling, and to design interventions to capture plastics large and small before they reach the environment. Worm notes that, like persistent organic pollutants (POPs), plastics in the environment are organic substances that accumulate in organisms and resist degradation. He cautions that although the proven effects of plastic contamination are physical and non-toxic, plastics may cause harm at a scale similar to POPs.[13]

II. FATE AND TRANSPORT

Crank out enough plastic bags, bottles, and food containers to serve the world's 7 billion people, don't collect or recycle more than a fraction, and pretty soon you have a planet shrink-wrapped in plastic. Plastics contamination has become so vast that future archaeologists could use plastic residues in the geological record as a marker of our modern "Plastic Age," according to a recent paper in *Science*.[14]

Scientists would like to know where all that plastic came from, and where it's going, so they can help devise policies to stop and even reverse the contamination, says Chelsea Rochman in a study in *Environmental Toxicology and Chemistry*.[15] It all starts with the plethora of lightweight, strong, and durable plastic in commerce. A recent study estimates that all of the plastic ever made since 1950 totals 8.3 billion metric tons. Of that total, roughly half was made since 2002. Yet the lion's share of plastic gets used once and tossed out. Since 1950, 6.3 billion metric tons of plastic waste has been generated. Only 9% of that waste has been recycled, and 12% was incinerated. Roughly 79% of the waste, or about 60% of all plastic ever made, has accumulated in landfills or the natural environment. If current trends continue, roughly 12 billion metric tons of plastic waste will be in landfills or the natural environment by 2050. Littered over the landscape or escaping from landfills, plastic trash ultimately makes its way to the sea.[16]

All Rivers Flow to the Sea, and So Does Plastic Trash

The Great Pacific Garbage Patch in the North Pacific occupies just one of the world's five subtropical gyres, where vortex-like ocean currents slow to a crawl. Cruising through the gyres in 2014, Marcus Ericksen of the Five Gyres Institute and his colleagues discovered that plastic pollution is indeed ubiquitous throughout the marine environment. The scientists sampled plastic floating on the surface, supplemented by visual surveys. Constructing a model of floating debris dispersal, the researchers estimated that there are more than 5 trillion pieces of plastic weighing over 250,000 tons at sea. When the team looked at different size classes of plastic, they were surprised to find much less microplastic at the sea surface than they expected, given how much plastic litter is expected to reach the ocean.[17] The findings have spawned a scientific debate about the missing plastic. Researchers speculate that microplastic at the sea surface is being removed by degradation from sunlight, ingestion by organisms, or colonization by microorganisms that make the plastic sink. On the other hand, sampling methods might be overlooking the smallest microplastics.

An April cover feature in *C&EN* reviews a landmark study from 2015:

> *"That's when a team led by Jenna Jambeck, an assistant professor of environmental engineering at the University of Georgia, published a paper titled, "Plastic Waste inputs from Land Into the Ocean" in Science. The team made assumptions about waste generation and probable plastics use in coastal populations around the world. Using the World Bank's country-level data on waste management practices, they estimated how much waste was mismanaged through improper collection and disposal. Finally, the team modeled how much of that mismanaged waste hemorrhaged into the ocean. The conclusion: between 4.8 million and 12.7 million metric tons during the basis year of 2010.*
>
> *The Jambeck paper suggests that plastics waste could reach crisis proportions if people don't come up with remedies more quickly than consumption increases. Plastics leakage to the ocean might grow to 17.5 million metric tons per year by 2025, and the cumulative buildup could hit 155 million metric tons by that time, doubling today's levels."*

Crucially, Jambeck observed that five countries—China, Indonesia, the Philippines, Sri Lanka, and Vietnam—contribute more than half of ocean plastics. Improve waste infrastructure in these places, and significantly less plastic will escape into the ocean overall.[18] Meanwhile, the Great Pacific Garbage Patch is growing exponentially. Laurent Lebreton, an oceanographer at the Ocean Cleanup Foundation, and his colleagues enlisted 18 boats to dip nets into the plastic debris and two planes to take images. Using the data to calibrate a transport model, the scientists predict that the patch contains at least 79,000 tons of plastic, a mass 4 to 16 times higher than previously reported. Containing mostly polyethylene and polypropylene, the patch is now 1.6 million km^2, about three times the size of France. Fishing nets make up more than 46% of the plastic load. Yet microplastics still seem to be missing from the area. The model predicted that there should be 100 times as much microplastic as the scientists actually found.[19]

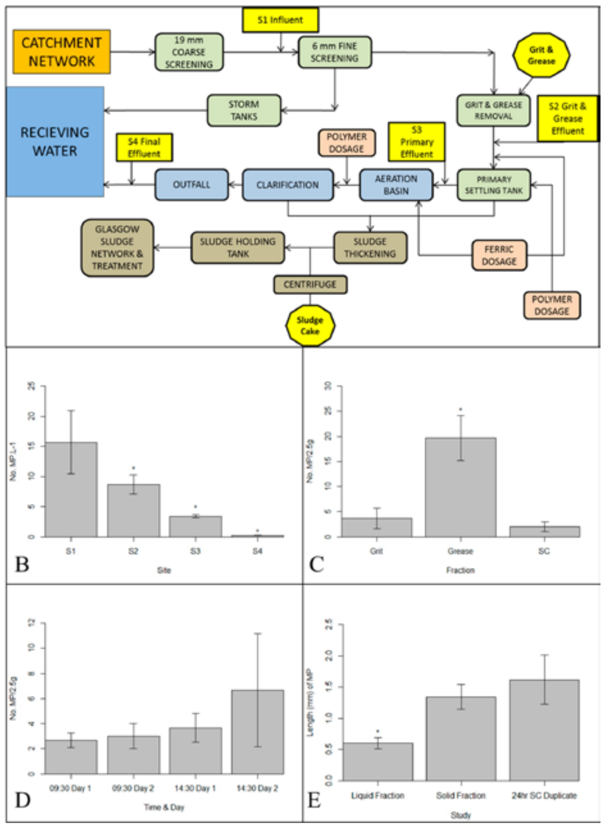
Until recently, estimates of land-based inputs of plastic into the sea have focused on the coast where most people live. Because rivers connect the global land surface to the sea, Christian Schmidt at the Helmholtz-Centre for Environmental Research and his team decided to estimate the amount of plastic flushed by rivers into the sea. The scientists combined plastic trash data from 1350 rivers and their watersheds to construct a model of plastic discharges. The researchers estimate that rivers carry as much as 4 million tons of plastic debris to the sea each year. The 10 top-ranked rivers transport up to 95% of the global load into the sea.[20] In a separate study, Lebreton found that two thirds of the plastic pollution comes from the top 20 rivers, led by China's Yangtze River, India's Ganges River, and a suite of other rivers in Asia.[21] Lebreton and Schmidt point out that their findings hint that resource managers could efficiently target just a few rivers to achieve dramatic reductions in plastic contamination of the oceans. "Reducing plastic loads by 50% in the 10 top-ranked rivers would reduce the total river-based load to the sea by 45%," Schmidt says.

In a recent *C&EN* article, Katherine Bourzac reports on the largest survey yet of microplastic particles in a freshwater system.[22] She writes, "Since the early 2000s, environmental scientists have studied the potential environmental effects of plastic microfibers, beads, and other fragments in the oceans. 'There's been much less attention on the terrestrial side of microplastics,' says Jamie Woodward, a physical geographer at the University of Manchester. 'There's hardly any data at all on microplastics in river systems.'"

Bourzac notes that scientists debate whether marine microplastic comes from rivers or from the breakdown of large pieces of plastic trash after they reach the ocean. So Woodward looked at all 10 of the rivers in northwest England that drain into the Irish Sea. The researchers found multiple contamination hotspots, with one location boasting about 517,000 particles per square meter—the highest concentration ever measured in freshwater. After winter-time record-breaking floods, the team sampled their sites again, finding a vast reduction in microplastic levels.[23] Bourzac writes, "Woodward believes that current models may be underestimating the concentration of microplastics in the world's oceans. About half of the seawater-buoyant microplastic pieces found in the Manchester study were smaller than 300 μm wide, and would pass through the nets used for marine microplastic counting studies, he says. Also the microplastic load flushed into the ocean in just the one flooding event in England accounted for a significant portion, about 0.5%, of the estimated total number of microplastic particles in the world's oceans, 4.85 trillion particles."

Scientists suspect that wastewater treatment plants could be a significant point source of microplastics in rivers and oceans. The plants are direct recipients of microbeads used in facial scrubs and toothpaste, microfibers washed off of synthetic clothing such as fleece jackets, and tire debris and fragmented plastics from urban runoff. Fionn Murphy of the University of the West of Scotland sampled microplastics at a secondary treatment plant serving a city of 650,000 people. Comparing water coming into and leaving the plant, he and his colleagues discovered that the treatment process sequestered 98% of particles entering the plant. The researchers determined that a large fraction of the microplastic floated into the greasy scum skimmed off the top of the effluent, and another large portion of the incoming microplastic eventually settled out into the sewage sludge. "In this study no microbeads were found in the final effluent," Murphy says. Despite the efficient removal of microplastics, the plant nevertheless discharged 65 million microplastics into the River Clyde in Glasgow every day. "Even a small amount of microplastic being released per liter can result in significant amounts of microplastics entering the environment due to the large volumes being treated," he says.[24]

While Murphy's sewage plant in Glasgow, Scotland, released effluent free of microbeads, not all treatment plants are so effective. Chelsea Rochman at the University of Toronto says that other studies report a range of 0–7 microbeads per liter of final effluent. "Fewer than seven



(A) Diagram of WwTW showing the location of the liquid fraction sampling sites (S1–4), where S1 = influent, S2 = grit and grease effluent, S3 = primary effluent, and S4 = final effluent. Sludge cake samples were taken from the same area for both the 24 h SC duplicate comparison and the comparison between grit and grease. (B) Barplot of the number of microplastic (MP)•L–1 at each liquid fraction site sampled (S1–4) (error bars = standard deviation, * = significance <0.05). (C) Barplot of the number of MP/2.5 g from solid fraction comparison (error bars = standard deviation, * = significance <0.05). (D) Barplot of the number of MP/2.5 g sample of 24 h SC duplicate (error bars = standard deviation). (E) Barplot of mean length of microplastic (mm) from each study (liquid fraction, solid fraction, and 24 h SC duplicate) conducted (error bars = standard deviation, * = significance <0.05).

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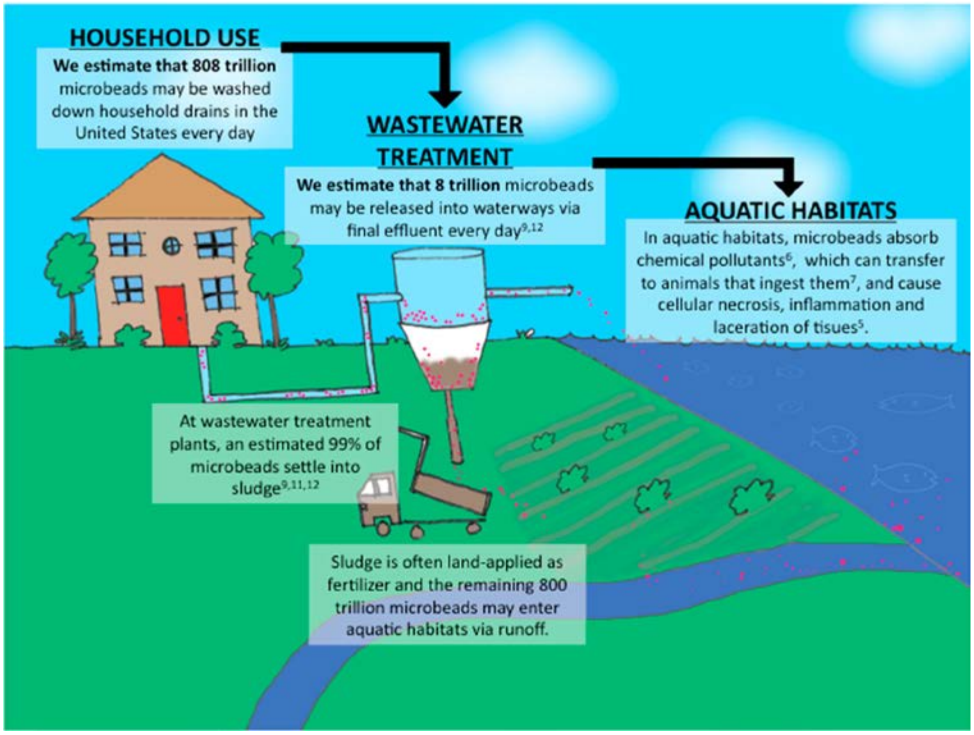
microbeads per liter of effluent may not sound significant; however, wastewater treatment plants in the United States are collectively capable of treating >160 trillion L of water every day," she says. Using a conservative estimate, she calculates that 8 trillion microbeads per day are emitted from wastewater treatment plants into aquatic habitats in the United States.[25]



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Delving into the release of microfibers from clothing, Nico Hartline washed polyester jackets in front-loading and top-loading washing machines. Levels of microfibers released ranged from 0 to 2 g per wash cycle, with top-loading washing machines leaching approximately seven times as many fibers as front-loading machines. Hartline estimated that a population of 100,000 people would send 1 kg of fibers each day to a sewage treatment plant, and that washing synthetic jackets could account for a substantial portion of the fibers observed in sewage influents.[26]

Another source of microplastics is sewage sludge. Luca Nizzetto reported that widespread application of sewage sludge on farmland likely represents a major input of microplastics to agricultural soils. "In Europe and North America about 50% of sewage sludge is processed for agricultural use," he says. He estimates that North American and European farmers apply up to 730,000 tons of microplastics each year in the form of sludge. This amount is more than the roughly 236,000 tons of microplastics estimated to reside in the world's oceans. The impacts are unknown, but microplastics could affect soil ecosystems, crops, and livestock through toxic substances leaching from the plastics. Farm soils, which are not well studied, could be the largest environmental reservoir of microplastics, according to Nizzetto.[27]

In a 2012 study in *Environmental Science & Technology (ES&T)*, Matthias C. Rillig was the first scientist to review the potential for microplastics to contaminate soil. He suggests that the lack of soil studies may stem from the fact that it is much more difficult to extract and quantify microplastics from soil compared to water. Potential sources of microplastics to soil include inputs from plastic mulch on farm fields, application of sewage sludge, litter, and deposition of air-born particles.[28]

Plastic Transports Contaminants Around the Globe

Scientists worry that plastic debris in the environment is soaking up hazardous pollutants, transporting them throughout the ecosystem and transferring the compounds to organisms that eat the plastic particles, potentially producing adverse health effects. Researchers are particularly concerned about pollutants in the water that are persistent, bioaccumulative, and toxic (PBTs), such as the pesticide DDT, the flame retardants known as polybrominated diphenyl ethers (PBDEs), polychlorinated biphenyls (PCBs) used in electrical transformers, and the polycyclic aromatic hydrocarbons (PAHs) formed from combustion. These hydrophobic compounds accumulate up the food web, leading to toxic effects at vanishingly small concentrations, says Richard Engler. Plastic and the PBTs are mutually attractive because they are both hydrophobic. The attraction is so great that plastic debris soaks up PCBs about 100 times better than naturally occurring materials such as sediment and algae.[29]

Each type of plastic absorbs pollutants differently, says Chelsea Rochman. As *C&EN* reported in August 2012, "Rochman and colleagues deployed pellets used to make five types of common plastics in San Diego Bay for up to a year. They retrieved samples at monthly intervals and used gas chromatography/mass spectrometry to measure concentrations of more than 50 persistent organic pollutants, including polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls."[30] The researchers found that HDPE, LDPE, and PP absorbed 10 times higher concentrations of organic pollutants than PET and PVC did.[31]

In a second study, Rochman and her team released virgin polystyrene (PS) pellets into San Diego Bay. The researchers showed that not only did the pristine pellets contain PAHs before they were deployed, but once in the water PS absorbed up to 200 times more PAHs than other kinds of plastics. The findings suggest that PS, used in disposable drinking cups, may pose a greater risk of exposure to PAHs than other plastics do when eaten by wildlife.[32]

Reaffirming Rochman's work and taking it a step further, Qiqing Chen found that plastic debris in the North Pacific Garbage Patch had significantly higher levels of PBTs than the surrounding water. Comparing the PBT concentrations to Canada's environmental quality standards for sediment, the researchers determined that 84% of the plastics they sampled had at least one chemical exceeding the standards. Noting that their sampling nets collected 180 times more plastic than biomass, the researchers suggest that marine life in the patch may be eating a significant amount of plastic. Sea turtles in the patch can consume up to 74% of their diet as ocean plastics. Chen proposes that plastic debris could be transferring PBTs to marine animals.[33] Yet the toxic hazards of plastic go beyond soaking up priority pollutants. In a 2013 *ES&T* article, Chelsea M. Rochman writes: "Last year, 150 tons of plastic pellets spilled off the coast of Hong Kong. The BBC reported, 'the plastic balls are not toxic on their own, but could absorb toxins that would be lethal to any species that might be tempted to eat them.' This highlights a common misperception regarding small plastic debris in aquatic habitats—the material itself is not considered a hazard to aquatic animals."[34] While many people consider plastic polymers inert due to their large molecular size, Rochman points out that more than 50% of plastics produced are composed of carcinogenic and endocrine-disrupting monomers such as styrene, polyvinyl chloride, or bisphenol-A. And many plastics contain risky chemical additives such as phthalates, nonylphenol, and flame retardants. As plastics degrade in the aquatic environment, they begin to shed monomers and chemical additives. Because reactions during production are rarely complete, plastics may also contain harmful solvents such as benzene or cyclohexane, which are free to migrate from the plastic and contact marine life.

As microlitter drifts through oceans and lakes, it accretes a slimy coating of bacteria and algae embedded in a matrix of lipids and proteins, says Christoph D. Rummel in a new study in *ES&T*. Researchers suspect that the coatings could affect fate and transport of the particles, but they don't have enough information. The biofilms might make the particles tastier to shrimp and tiny aquatic insects, facilitating entry to the food web. The films could metabolize contaminants or help accumulate and transport them throughout the environment. Ominously, some scientists have detected pathogenic Vibrio bacteria that cause foodborne infections on floating microplastic, but it is unknown whether microplastics boost the rate of infection of humans.[35]

III. ANALYTICAL METHODS

In 1971, Edward J. Carpenter of the Woods Hole Oceanographic Institution was cruising through the Sargasso Sea in the North Atlantic when he and his team discovered plastic pellets and fragments in all their surface net samples. His seminal papers on the findings launched a host of studies on plastic litter at sea.[36]

For the next several decades, scientists focused on harm to wildlife from ingesting and getting entangled in plastic trash such as fishing gear and six-pack holders. But attention returned to microscopic plastic in 2004 when Richard C. Thompson at the University of Plymouth documented high levels of small plastic particles in the Northeast Atlantic Ocean. Dubbing the particles "microplastics" for the first time, his paper in *Science* marks the beginning of rapidly growing efforts to monitor microplastics in the environment.[37]

Methods of defining, sampling, and quantifying plastics in the environment are crucial to understanding their impacts. Yet experts point out that the many fine studies on plastics use a hodgepodge of methods and definitions, making it difficult to draw a global picture of plastic waste from the wealth of available data. These experts have a long list of recommendations to improve analytical methods, beginning with a better definition of microplastics.

What are Micro- and Nanoplastics?

Some microplastics are intentionally manufactured for use as industrial abrasives and facial scrubs, or as the production pellets known as nurdles, destined to be melted and molded into plastic products. Yet the vast majority of microplastics in the environment come from the breakdown of larger plastic objects. Blasted apart by UV radiation and torn up by abrasion or wave action, plastic trash eventually breaks down into micro- then nano-sized particles.[38]

Many researchers define microplastic based on the methods used to capture and visualize it. In 2008, the U.S. National Oceanic and Atmospheric Administration (NOAA) argued that microplastics are particles larger than 333 µm, the mesh size of nets, and smaller than 5 mm, the lower limit of detection with the naked eye.[39] This definition leaves out micrometer-sized debris that is smaller than 333 µm. In a report in *ES&T*, Valeria Hidalgo-Ruz subdivides microplastics into a large size class, 500 µm to 5 mm, and a small size class, less than 500 µm. Other researchers have suggested that large microplastics should range from 1 mm to 5 mm in size, and small microplastics should range from 20 µm up to 1 mm in size.[40]

Nanoplastics have recently grabbed the attention of scientists because, in addition to sharing the chemical characteristics of larger plastic bits, nanoplastic may acquire novel traits simply due to its size, enabling it to easily penetrate and irritate cells. Yet researchers are hampered by two major technical problems: there is no clear consensus on the definition of nanoplastic size, and there is currently no rigorous methodology to detect the tiny particles in the environment.[41]

For nanoplastics, researchers have largely borrowed the definition of manufactured nanoparticles: a microscopic particle with at least one dimension less than 100 nm.[42] But Julien Gigault at the Université de Rennes proposes to define nanoplastics as particles unintentionally produced and presenting a colloidal behavior, within the size range from 1 to 1000 nm.[43] In contrast, the European Commission has described nanoplastics as any particle that is 1 to 100 nm in at least one dimension.[44]

Antony J. Underwood concludes in *Analytical Methods* that terms for different sizes of debris ought to conform to the International System of Units[45] based on their diameter, with nanoplastic referring to nanometer-sized debris, microplastic referring to micrometer-sized debris, milliplastic referring to millimeter-sized debris, and centiplastic referring to centimeter-sized debris.[46]

Sampling Strategies

Because plastic contamination is a global problem, scientists would like to gauge the amount of plastics in the environment, track hotspots, and monitor trends. Answering these important questions depends on consistent, accurate, and standardized sampling methods, which experts say are lacking today.

Hoping to gain a picture of plastic trash along ocean coastlines, Mark Anthony Browne reported in *ES&T* on an analysis of 104 scientific papers on marine debris. Stymied, he found that the studies used such different methods with regard to what, where, when, and how the samples were taken that the data were not comparable and could not answer his questions. Some researchers measured standing stocks of debris while others determined rates of accumulation over days or months. Most sampled only beaches, not rocky shores or mangroves. Some sites were upwind while others were downwind. And too often the sampling method wasn't described or wasn't repeated enough to provide statistical rigor. To improve data collection, Browne recommends sampling to be standardized and also undertaken on a large and long-term scale by international collaborations of scientists.[47]

Sampling surface water for microplastic hasn't changed much since the first studies in the 1970s. Scientists attach nets of varying sizes to their boats. Depending on the sampling device, the researcher will measure plastic from different overlying layers of the water. Researchers at the Korea Institute of Ocean Science and Technology decided to systematically compare different sampling methods in a report in *ES&T* in 2014. Because microplastics are buoyant, the scientists focused on the surface microlayer, the top 400 µm of ocean water. The team investigated four different sampling methods, including a metal sieve, a plastic bucket, a hand net, and a trawl net, collecting a different portion of the surface microlayer with each method. The metal sieve method captured the most microplastic, nearly 350 times as many particles per cubic meter as the trawl net, which was the least efficient method. Although popular among researchers, trawl nets are likely underestimating the amount of microplastic in the surface layer of water.[48]

But the choice of net is not the only problem with collecting microplastics. A recent study in *Analytical Methods* recounts a litany of sampling mistakes. A. J. Underwood writes, "Some of the sampling is to consider large-scale patterns. Some is to gather information about temporal trends. Regardless of the objectives, much of the sampling is not adequate to provide robust data to allow comparative assessments, examine trends or, in some cases, even to be sure about the quantities of plastic being encountered." Because microplastics naturally contaminate the air, reagents, equipment and clothing, scientists must use controls to account for contamination. Remarkably, researchers are still using equipment that is made of plastic or cannot be cleaned.[49]

While investigators often scoop up water, sediments and beach samples, they rarely examine sea beds for microplastics, making that habitat ripe for exploration, Underwood says. In fact, the lack of studies of microplastics in a variety of habitats makes it difficult to develop a global picture of their prevalence. Underwood explains that habitat and environmental factors matter: sandy shores can accumulate more plastic pellets than do adjacent rocky shores; microplastic concentration varies with distance from sewage outfalls, urban areas, and commercial activity; winds, currents, and rain runoff can all affect the amount of plastic accumulating at any one location. Scientists need to structure their sampling so that it takes these factors into account, he says.

Yet researchers continue to use unreliable research methods to measure the presence of microplastic. They have used different sampling methods while trying to compare different habitats. Other scientists chose beaches for sampling based on their close proximity to easy parking near urban centers that are abundant sources of microplastics. Thus, the data would overestimate the amount of microplastics across a region, Underwood says.

Identifying Plastics

Back in the lab with their jars of sediment or seawater, scientists must now separate the plastic from all the sand, mud, shells, glass, algae, and fish scales in the samples. Most researchers take advantage of the fact that plastics float, while sand and sediment sink.

So scientists mix the sample with their solution of choice, shake it up, and wait for the sediment and other heavy materials to settle out while the plastic floats to the top or remains suspended in solution. Popular solutions include concentrated saline (NaCl), sodium iodide (NaI), sodium polytungstate ($Na_6O_{39}W_{12}$), zinc chloride ($ZnCl_2$), zinc(II) bromide ($ZnBr_2$), and seawater, each with a different density targeted to different plastics. Researchers then extract the plastic particles by passing the solution over a filter, usually aided by a vacuum.[50]

Scientists often digest seawater samples with acids or enzymes to remove unwanted organic detritus such as algae, crustaceans, and bacteria that have adhered to the plastic bits. Some researchers conduct a two-part digestion using hydrogen peroxide followed by hydrofluoric acid. Other investigators say that they can recover 85 to 91% of the plastic particles after density separation and extraction. But many studies do not report on the exact procedures used or the recovery rate of microplastics, even when digestion methods have the potential to damage the structure or physical characteristics of plastic polymers. Ideally, scientists should spike samples with known kinds and amounts of plastic polymers to monitor the efficiency of the process and to track any changes in chemical composition after treatment, says Michaela E. Miller, a technical officer at the Australian Institute of Marine Science.[51]

Teasing plastics out of animals such as blue mussels, sardines, and common buzzards requires a slightly different approach. Most researchers freeze biological samples at –20 °C to stop any chemical or biological agents from altering the plastic. Other scientists use cocktails of formaldehyde-based fixatives or ethanol to preserve tissues. Because microplastics get trapped inside tissues and thus evade detection, researchers digest biological samples with acidic, oxidative, and alkaline compounds such as nitric acid (HNO_3), peroxide (H_2O_2) and sodium hydroxide (NaOH).[52] But these kinds of chemical digestions can destroy plastic particles and their surfaces. A recent study in *ES&T* reports success by treating samples with a series of technical-grade enzymes that digest proteins, cellulose, and chitin, the material found in crustacean shells.[53]

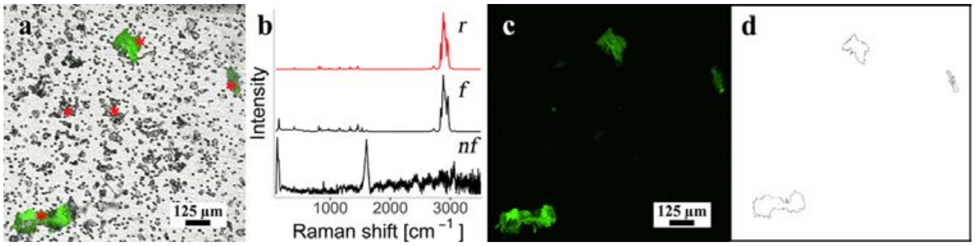
Yet even the apparently plastic-safe enzyme treatments will redeposit dissolved tissue residues on plastic surfaces, making it more difficult to measure the plastics. As a solution to this problem, Jeff Wagner at the California Department of Public Health and colleagues decided to apply sound waves to fish guts to retrieve the plastic hidden inside. The team hit the guts with a series of ultrasonic bursts, releasing plastic particles from the tissues while leaving the guts intact. The scientists detected mainly polyethylene and polypropylene in the stomachs of ocean-caught lanternfish from the family Myctophidae. "One nearly empty lanternfish stomach contained a long polyethylene fiber that appeared to block the digestive tract," Wagner reports.[54]

After separating and extracting the plastic, researchers sort through a concentrated sample of fragments in a multitude of colors and ranging in size from the microscopic to the visually detectable. Tediously, the investigators count and identify plastic fragments in the 1–5 mm size range with the naked eye and use optical microscopes for particles in the hundreds of micron range. But up to 70% of particles that visually resemble microplastics are actually something else, such as shell fragments, natural fibers, or minerals. Since scanning electron microscopy can't always characterize the polymers in the tiniest micro- and nanoplastics, Valeria Hidalgo-Ruz of Chile's Universidad Católica del Norte recommends that researchers apply chemical analytical techniques such as Fourier-transform infrared (FTIR) spectroscopy and Raman spectroscopy.[55] And scientists can identify polymers in microplastics as small as 10 μm with the use of micro-attenuated total reflectance–FTIR (μ-ATR–FTIR), which observes particles microscopically prior to spectroscopic fingerprinting.[56]

Eager to look for microplastics in municipal wastewater, Alexander S. Tagg at Brunel University London and his colleagues decided to try focal plane array (FPA)-based micro-FTIR spectroscopy. This enhancement to FTIR simultaneously acquires thousands of spectra within minutes, allowing semi-automatic identification of microplastics. The new method correctly identified 98.33% of the microplastic fragments in the organic-rich effluent. "The success of this methodology means that the abundance of microplastics in wastewater can now be examined to further our understanding of how microplastics enter the natural environment," Tagg says.[57] Researchers have automated micro-FTIR spectroscopy even further by adding image processing software.[58]

A new study turned to Raman spectroscopy to identify microplastics in seawater and the stomachs of Atlantic and Pacific Ocean fish. Similar to FTIR, Raman analysis measures light scattered off of molecules to create a unique fingerprint of individual plastic polymers. The smaller light beam used in Raman spectroscopy offers detection of plastic particles down to 1 μm in size.[59] Yet Raman and FITR spectroscopy are time-consuming. A new study in the *Journal of Raman Spectroscopy* shows that stimulated Raman scattering (SRS) microscopy can identify microplastics 1,000 times faster than conventional Raman spectroscopy.[60]

Gabriel Erni-Cassola at the University of Warwick has taken the tedium out of sorting plastics with a fluorescent-dye technique to detect plastic particles less than 1 mm in size. The dye, Nile red, specifically binds to plastic particles, rendering them easily visible under a fluorescence microscope. A software program quantifies the glowing particles, allowing for accurate and rapid analysis of large numbers of samples. Testing their method with samples taken from the seawater around Plymouth, England, the scientists found significantly more small microplastics than would have been identified with traditional methods. Most of the small microplastics were polypropylene, a polymer used in packaging and food containers. Previous studies had found dramatically lower than expected numbers of small microplastics after performing a global survey of sea surface plastic debris. The research team proposes that the low incidence of small microplastics observed by the earlier studies might be due to the methods used in those studies to identify and select the particles.[61]



Microscope images of processed sand samples demonstrating selective Nile red fluorescent staining of synthetic polymers with Raman spectra of scanned particles. (a) Composite image of excitation and emission at 460 and 525 nm, respectively, and bright field. Asterisks indicate particles assessed via Raman spectroscopy. (b) Normalized Raman spectra obtained from particles highlighted in panel a: r, PP (Sigma-Aldrich) spectrum; f, typical spectrum of a fluorescent particle in panel a; nf, typical spectrum of a nonfluorescing particle in panel a. (c) Field shown in panel a using green fluorescence only. (d) ImageJ drawing depicting >400 µm2 particles that were quantified via our macro.

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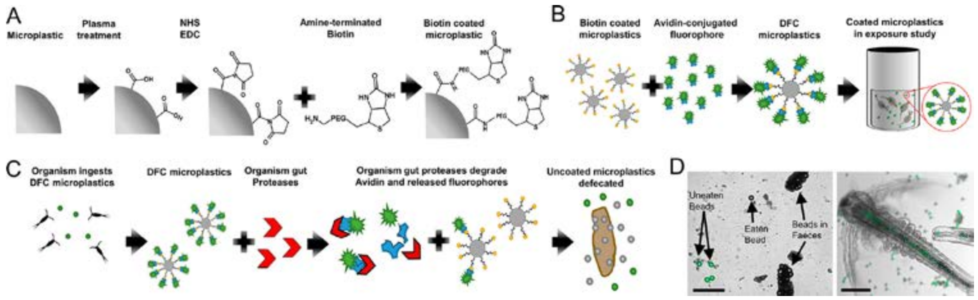
DOI: 10.1021/acs.est.7b04512

Researchers at the University of Toronto recently took advantage of fluorescence to measure how much microplastic is eaten by tiny marine crustaceans called copepods. The scientists fed copepods plastic fragments coated with a digestible fluorescent dye. At the end of the experiment, they confirmed that any plastic fragment still retaining its fluorescent coating had not been consumed by the copepods. The large amounts of data generated by the team were quickly analyzed using multichannel microscopy and automated particle counting with image analysis software. “This method can be used to answer several questions, including how many plastics are ingested, whether animals prefer a certain type, shape or size of microplastic, and how feeding behavior varies among species,” the authors say.[62]

But the bottom line is that different ways to identify and count microplastics will yield different results that can’t be compared across studies, says Michaela Miller at the Australian Institute of Marine Science. She calls for scientists to work toward a single reliable, standardized, and efficient approach.



Methods and Concept. (A) Plastic preparation: coating plastics with biotin; NHS: N-hydroxysuccinimide; EDC: N-(3-(dimethylamino)propyl)-N′-ethylcarbodiimide hydrochloride. Amine-terminated biotin: poly(ethylene glycol) 2-aminoethyl ether biotin. (B) Bead coating: binding fluorescein–avidin conjugate to biotin on plastic surface. (C) Dye degradation mechanism: depiction of how bead fluorescence decreases when microplastics are ingested and passed. (D) Images of beads passed and in organism gut. Plastic: 13.0–17.9 μm polystyrene microbeads in *A. salina*. Scale bars are 200 μm.

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DOI: 10.1021/acs.estlett.7b00545

IV. WILDLIFE AND HUMAN HEALTH EFFECTS OF PLASTIC DEBRIS

Plastic trash litters beaches, oceans, lakes and farmlands in stupefying volumes. The sheer scale of the contamination has grabbed the attention of governments that are beginning to take steps to curb the tide of plastic discards. But some observers suggest that governments have not unleashed the full force of existing laws, because they are uncertain about the nature and extent of the risk of plastic debris to humans and the ecosystem, according to Chelsea Rochman in a 2016 paper in *Ecology*.[63]

Rochman goes on to explain that under legislation in the U.S. and the European Union, if materials are classified as hazardous, governments can use existing laws to eliminate sources of the materials and find safer alternative products. Yet, materials are not considered hazardous until research demonstrates with certainty that a substance harms humans, wildlife, and the environment. To address this knowledge gap, scientists are rapidly building a body of work documenting the risks of plastic debris ranging from large, visible floating trash to the tiniest particles suspended in oceans and lakes. Perhaps the best documented harm comes from marine macro-litter.

Nets, Bags and Straws Harm Wildlife

A dead sperm whale washed up on Spain's Murcia Coast in February of this year, carrying 29 pounds of plastic in its stomach and intestines. The El Valle Wildlife

Rescue Center concluded that the plastic nets, ropes, and sacks that the whale ate blocked its gut, resulting in the infection that killed it.[64]

The whale was just one member of at least 560 species that have run afoul of plastic discards, according to a recent study. Beginning in the 1960s, researchers have recorded hundreds of thousands of individual animals entangled in plastic or having swallowed plastic debris often mistaken for food. Entanglement almost always results in direct harm or death due to amputated limbs, suffocation, or inability to obtain food. At least 17% of affected species are listed as threatened or near threatened by the International Union for the Conservation of Nature (IUCN). All species of sea turtles, two-thirds of all marine mammal species, and half of all seabirds are affected by marine debris, the authors say.[65] Other findings indicate that worldwide between 57,000 and 135,000 seals and baleen whales are entangled each year.[66]

A study by Qamar A. Schuyler in *Global Change Biology* estimates that up to 52% of all sea turtles may have ingested debris. When animals eat plastic, the debris slows digestion and takes up space, preventing the optimum intake of food and weakening the animal. In the worst case, ingested debris such as drinking straws can block or perforate the gastrointestinal tract, resulting in death. The scientists pinpointed the regions of highest risk to sea turtles including the east coasts of the U.S., Australia, and South Africa, the East Indian Ocean, and Southeast Asia.[67]

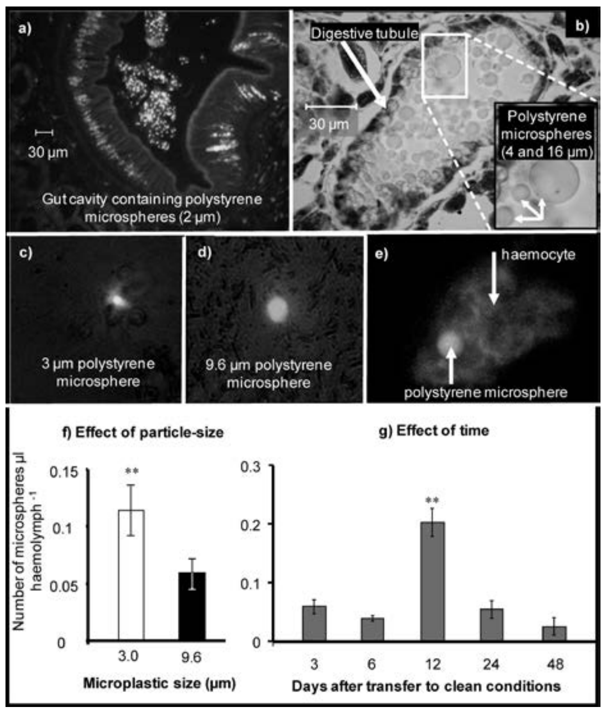
Researchers have compiled considerable evidence of harm to individual organisms and threats to species. But it is difficult to show whether the threats have ecologically relevant impacts such as reducing population size or changing the species composition of natural communities. In an effort to provide a preliminary basis for evaluating the impact of debris on marine animals, Chris Wilcox and colleagues surveyed 274 scientists, asking about the impact of marine litter on seabirds, turtles, and marine mammals. Respondents said that fishing pots, lines, traps and nets, balloons, and plastic bags posed the greatest entanglement risk to animals. When it comes to the hazards of ingesting trash, plastic bags, straws, and utensils topped the list. The findings suggest that manufacturers should redesign fishing gear and regulators need to combine economic incentives with penalties for littering fishing gear to reduce the threat of entanglement. Identified as one of the greatest threats to ocean wildlife, plastic bags warrant the bans recently put in place by many governments, Wilcox says.[68]

Scientists have produced sparse evidence of impacts on populations or assemblages of species. In one study, researchers revealed that plastic macro-debris has smothered the marsh grass *Spartina alterniflora*, completely eliminating vegetation in some areas.[69] New research by Joleah B. Lamb surveyed 159 coral reefs in the Asia-Pacific region and found that corals in contact with plastic had an 89% chance of contracting diseases that eat coral tissue and typically result in death. Plastic-free corals had just a 4% chance of getting ill. Lamb speculates that the plastic might stress corals by shading them from the sunlight they need to make food or by scratching them, thus creating points of ingress for pathogens. Also, the debris is known to provide habitat for disease organisms and could be helping the bacteria reach the corals.[70]

Wildlife Ingest Little Poison Particles

Microplastics soak up hazardous compounds from the water, then animals of all kinds, from microscopic crustaceans to fish and seabirds, ingest the microplastics. But can sea life absorb hazardous chemicals from the plastic, and, if so, does it make any difference? A pair of influential papers published in *ES&T* a decade ago presented persuasive data that microplastics can impact marine food chains. Emma Teuten used a model in 2007 to show that common marine lug worms can accumulate the PBT phenanthrene from microplastic particles.[71] Mark Browne's 2008 paper confirmed that *Mytilus edulis* mussels fed microplastic fragments accumulated the plastic bits in their guts. Within three days, the particles moved from the gut into the mussel's circulatory system and remained there for more than 48 days.[72]

More recently, researchers have documented the transfer of PCBs from microplastics to mud-dwelling marine worms[73] and seabirds.[74] However, another study on Norwegian seabirds found that microplastics acted more like passive samplers, reflecting the concentrations of POPs in the birds' gut.[75]



Uptake of plastic particle by *Mytilus edulis* (L.). (a) Tissue section (4 µm thick) containing 2 µm and (b) 4–16 µm polystyrene microspheres in the gut cavity and digestive tubules. 3.0 (c) and 9.6 µm (d) polystyrene microspheres in the hemeolymph and (e) hemocytes. Significant differences in accumulation in the hemeolymph according to (f) "particle-size" and (g) "time" at $P < 0.01$**. N.B. Values are expressed as mean ± SE and calculated from independent data from each time/treatment/replicate combination and are therefore are cumulative.

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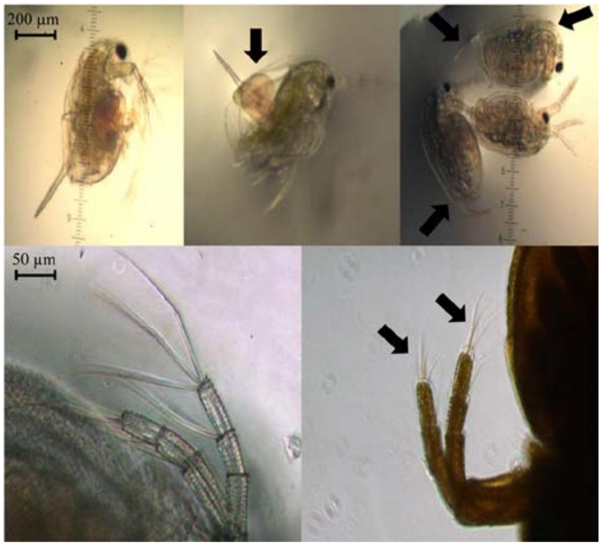
DOI: 10.1021/es800249a

Because fish are ecologically important and sensitive indicators of aquatic stress, researchers at the University of California, Davis decided to test the response of Japanese medaka (*Oryzias latipes*) to a diet of polyethylene microplastic. The scientists marinated polyethylene pellets in San Diego Bay to pick up a cocktail of PAHs, PCBs, and PBDEs, then fed it to the fish. The fish bioaccumulated the pollutants and experienced hepatic stress, likely due to both the plastic material and the contaminants it soaked up from the bay.[76] In a follow-up study, the researchers again fed Japanese medaka environmentally relevant concentrations of polyethylene microplastic deployed in San Diego Bay. This time, the scientists were looking for altered expression of genes that are indicators of exposure to estrogenic or anti-estrogenic substances. Plastic-associated chemicals such as styrene, bisphenol-A, and phthalates can disrupt endocrine function, as can contaminants picked up from the bay such as pesticides and heavy metals. Both male and female fish fed the marine plastic diet experienced altered expression of the indicator genes.[77]

Another pair of studies in *ES&T* help validate concerns that microplastics could be having ecological effects such as stunting growth and depressing reproduction of aquatic organisms. When Matthew Cole exposed copepods to a mix of algae and polystyrene beads, the tiny crustaceans consumed 40% less carbon biomass from the algae and produced smaller eggs with reduced hatching success.[78] Ellen Besseling exposed a green algae, *Scenedesmus obliquus*, and the small crustacean *Daphnia magna* to nano-polystyrene. She and her team found, for the first time, that nanoplastic reduced population growth and chlorophyll levels in the algae, while the exposed *Daphnia* were smaller in size and their offspring were malformed.[79]



Malformations in different developmental stages of Daphnia neonates. Top-right: incomplete developed antenna setae, curved shell spine and vacuoles around ovary. Top-middle: lump in the carapace. Top-left: normal developed neonate. Bottom-right: short antenna setae. Bottom-left: normal developed antenna setae. The arrows depict malformed body parts.

Reprinted in part from: *Environ. Sci. Technol.*, 2014, 48 (20), pp 12336–12343

DOI: 10.1021/es503001d

Alexander H. Tullo interviewed Britta Denise Hardesty, a principal research scientist with

Australia's Commonwealth Scientific & Industrial Research Organisation, for a cover story in *C&EN*. She told Tullo, "It is reasonable to think that if we continue in the direction where we are going now, there's going to be ecosystem impact. Plastics don't belong in our stomachs, in our food chain, or over our reefs. That stuff smothers and kills things."[80] Tullo writes, "Hardesty recently participated in a study that dissected 378 seabirds in eastern Australia. Some 24% of them had debris in their digestive tracts. She helped compile a survey of published data suggesting that, by 2050, 95% of all seabirds will be ingesting plastic if the pollution isn't mitigated."Tullo also reports, "Chelsea Rochman, assistant professor in the department of ecology and evolutionary biology at the University of Toronto, sees similarly alarming trends in fish. She led a 2015 study in which researchers bought fish at markets in Indonesia and California and dissected them to see if they could find microplastics—less-than-5-mm fragments that result when the environment shreds littered plastics over time. She found microplastics in 28% of the 76 fish from Indonesia. She also found debris in 25% of the 64 fish procured in California. In the U.S., most of the waste was microfiber, possibly from laundry water."

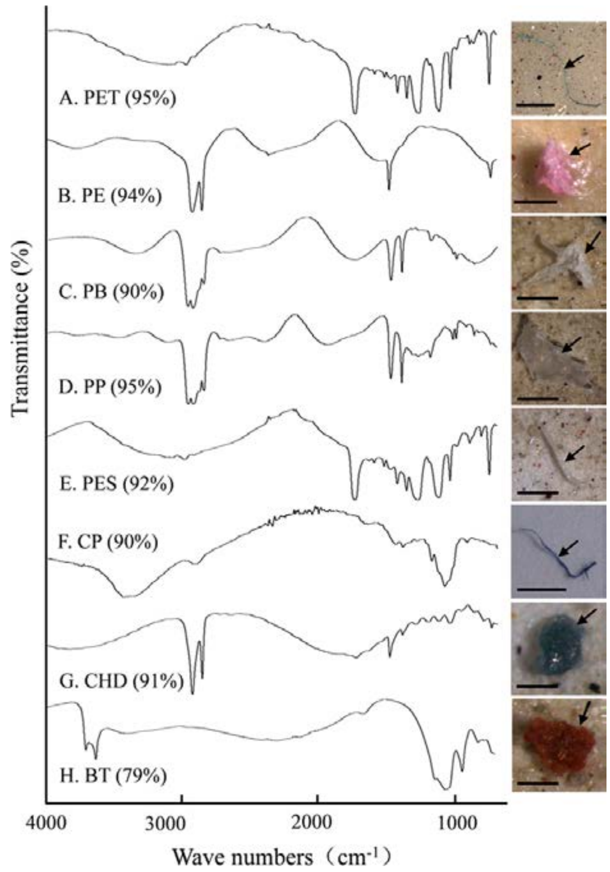
"Today, there remains no doubt that plastic debris contaminates aquatic (marine and freshwater) habitats and animals globally," Rochman writes in a 2016 study in *Environmental Toxicology and Chemistry*. She and her co-authors say that although it is difficult to prove ecological impacts at the levels of populations, there is a growing body of research that presents enough evidence for governments to act.[81]

Humans Eat, Drink, and Inhale Plastic

Emerging contaminants evolve along a familiar trajectory. Scientists detect widespread contamination of air and water with potentially harmful substances, track their movement into wildlife and establish risk to human health. Once the threat to human health is affirmed, bans and regulations ensue, as happened with substances such as PBDE flame retardants and the plastic monomer bisphenol-A. Microplastics are firmly entrenched as an emerging contaminant. Yet the final piece in the puzzle—determining whether there is a threat to human health—is still in the very early stages of development. Researchers must assess how much plastic humans take in through the food we eat and the air we breathe, quantify exposures to our cells and tissues, and compare the contribution of microplastic to all the other harmful exposures humans encounter in daily living.

A new study in *ES&T* by Stephanie L. Wright reviews what scientists know about dietary exposures to microplastics. She reports that scientists found microplastics in all 24 samples of German beer that they tested. One sample contained up to 109 plastic fragments per liter.[82] Because sea salt is derived from seawater contaminated by plastic, researchers from China decided to look for microplastics in 15 brands of sea salt purchased in China. The scientists found up to 681 fragments of microplastics per kilogram of salt, with PET being the most common type contaminating the salt.[83]

A 2017 literature review from the UN's International Maritime Organization concluded that 89 species of fish have ingested microplastics. Of those, 49 species are favorites on our dinner plates, including bluefin tuna, albacore, Atlantic herring, and anchovies. The studies on fish have been limited to examining microplastics in the gut and have not evaluated how long the plastic stays in the stomach or whether it is transferred to tissues that people like to eat.[84]



Analysis of microplastics with micro-FT-IR. Abbreviations: BT, bentonite; CP, cellophane; CHD, cyclohexane derivatives; PB, poly(1-butene); PE, polyethylene; PP, polypropylene; PES, polyester; PET, polyethylene terephthalate. The value in the brackets indicates the matches of the spectra with the standards. The black arrows in the photographs indicate the particles that were identified. Scale bar = 0.5 mm (A) or 0.25 mm (B–H).

Reprinted in part from: *Environ. Sci. Technol.*, 2015, 49 (22), pp 13622–13627

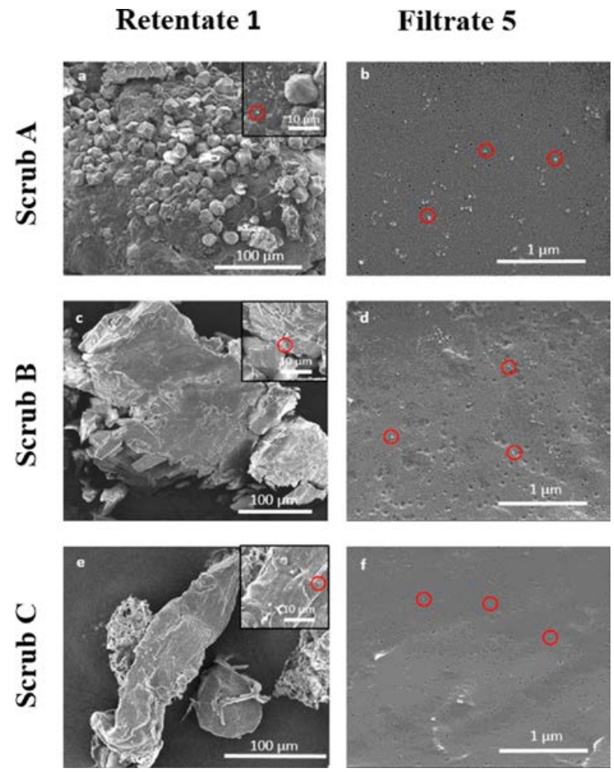
DOI: 10.1021/acs.est.5b03163

However, people do like to eat shellfish whole and therefore cannot avoid eating the microplastics that might accompany these morsels. The UN review says that scientists have observed microplastics in mussels, clams, oysters, and scallops. The plastics ranged in size from 5 µm to 5 mm and consisted mainly of fibers, followed by fragments and pellets. One study found an average of 178 fibers in each farmed mussel.

After a seafood meal, diners seeking to quench their thirst with water could find themselves imbibing more plastic, according to a pair of new studies sponsored by Orb Media, a nonprofit journalism organization.[85] Scientists from the University of Minnesota and the State University of New York at Fredonia analyzed tap water from 14 countries. The researchers found that 83% of the water samples contained plastic, averaging 4.34 particles per liter. The majority of particles consisted of fibers ranging in length from 0.1 to 5 mm. The authors estimate that a man would consume 4,000 particles a year from tap water alone.[86] In a follow-up study published this year, the team sampled 259 bottles of water purchased in nine countries from major brands such as Nestlé. The researchers found microplastics in 93% of the bottles, averaging 10.4 particles per liter, double the levels found in the tap water.[87]

In addition to drinking and eating, it's also a good bet that humans inhale microplastics. Scientists have observed the atmospheric fallout of microplastics in Paris, averaging 110 particles/m2/day. Synthetic fibers accounted for most of the particles.[88] Researchers don't know what happens to microplastic fibers once they are inhaled, but speculate that humans will eject most of the fibers from the lungs through coughing or clearing the throat. However, some fibers could persist, causing inflammation and potentially releasing additives and POPs that might lead to cancer and gene mutations.[89]

Skin is the largest human organ and potentially provides an entry route for nanoplastics in cosmetic and personal care products such as shampoos and facial scrubs, according to a recent study in *ES&T* by Laura M. Hernandez. She and her team sampled three commercial facial scrubs containing polyethylene microbeads and used sequential filtration followed by scanning electron microscopy to reveal for the first time the presence of nanoplastics less than 100 nm in size in the scrubs. Although microbeads



SEM images of samples taken at different filtration steps of the commercial scrubs: (a) retentate 1 from scrub A, (b) filtrate 5 from scrub A, (c) retentate 1 from scrub B, (d) filtrate 5 from scrub B, (e) retentate 1 from scrub C, and (f) filtrate 5 from scrub C. Samples of retentate 1 for each scrub were dried and fixed onto carbon tape for imaging. Samples of filtrate 5 for each scrub were filtered through 10 nm polycarbonate membranes for imaging.

Reprinted in part from: *Environ. Sci. Technol. Lett.*, 2017, 4 (7), pp 280–285

DOI: 10.1021/acs.estlett.7b00187

have been banned in North America and Europe, they are still widely used in many other countries.[90]

Humans are exposed to microplastic in food, water, and air, but are those microplastics penetrating tissues and causing problems? In a recent review article, Messika Revel describes studies in dogs and rodents showing that microplastics can travel across gut tissues and enter the body. In mouse liver, microplastics appeared to induce alteration of oxidative stress, energy, and fat metabolism.[91] In her review, Wright notes that the medical literature widely documents inflammation resulting from polyethylene and polyethylene terephthalate particles abraded off of prosthetic implants such as artificial joints. Based on wildlife studies, scientists speculate that the chemicals added to or picked up by plastics could also be transferred to humans that ingest the plastics. In fact, a laboratory study found that chemical contaminants were released from microplastics up to 30 times faster in the simulated digestive environment of a warm-blooded organism than they were in seawater, Wright says.

A recent review cautions that the actual risks of microplastics are unknown and may be significantly less than other environmental exposures.[92] Yet Engler points out that for people living in the U.S. and Japan, their total daily intake of PCBs is approximately at the tolerable threshold set by the World Health Organization. He argues that because microplastics can transfer PCBs from the water into the marine food web, and since fish is an important source of PCBs in the human diet, that there is no “room” for an additional PCB burden in fish and humans from microplastics.[93] Although humans are likely exposed to low levels of plastic and its accompanying chemical contaminants, it is still important for scientists to provide answers about exposure levels and the toxic impacts of microplastics, Wright concludes.

V. RE-ENVISIONING PLASTIC

The U.S. government granted Swedish engineer Sten Gustaf Thulin a patent for the first plastic bag with handles on April 27, 1965. Half a century later, the convenient bags now cause more harm to marine life than any other macroplastic litter. Enduring for hundreds to thousands of years, plastic bags along with other plastic discards have become an environmental concern prompting government interventions across the globe that are already helping to curb the amount of plastic debris in the environment.[94]

Bans and Taxes

Successful campaigns combine taxes and bans on plastic, as recommended by the Honolulu Strategy, developed by the UN Environment Program and the U.S. National Oceanic and Atmospheric Administration. For instance, China in 2008 prohibited stores from providing free plastic bags less than 0.025 millimeters thick. Supermarkets subsequently reduced plastic bag use by up to 80%.[95] After the United Kingdom introduced a £.05 charge on plastic bags in 2015, shoppers used 6 billion fewer bags during the first year of implementation, representing an 85% drop.[96] Just three years later, a new study credits the charge with improving the health of the seafloor. Data collected by scientists reveals a decline of nearly 30% in plastic bags on sea beds off the British coast.[97] Meanwhile, California is touting the success of its plastic bag ban, implemented in January 2012. Data collected from the state's 2017 Coastal Clean-up Day shows a 72% drop in plastic bag litter compared to 2010.[98]

When scientists raised the alarm about plastic resin preproduction pellets known as nurdles littering shorelines around the world, the plastics industry launched Operation Clean Sweep to achieve zero loss of plastic pellets by manufacturers. In the U.S., California implemented a regulation decreeing zero tolerance for nurdle littering in 2008. Since then, researchers have recorded a significant decrease in nurdle contamination of the environment.[99] In one recent study reported in *ES&T*, Chelsea Rochman writes, "Public support for banning microbeads is growing and has prompted action from multinational companies, NGOs [nongovernmental organizations], and policy-makers. For instance, Unilever, The Body Shop, IKEA, Target Corporation, L'Oreal, Colgate/Palmolive, Procter & Gamble, and Johnson & Johnson pledged to stop using microbeads in their 'rinse-off personal care products,' and more than 70 NGOs from more than 30 countries are working on or helped pass legislative action to ban microbeads from personal care products."[100] Legislation to ban the bead has been introduced in the U.S., Canada, the European Union, and Australia. Rochman urges scientists to begin measuring the effectiveness of these bans. Because debris gets transported to the shoreline via rivers and storm drains, several jurisdictions have taken aim at these entry point sources. Korea has installed trash booms in major rivers and waterways to trap and remove plastic trash before it reaches the sea. U.S. cities along the Anacostia River in Maryland and the Los Angeles River in California have set a total maximum daily load of trash that is allowed to enter the water from land.[101]

A Circular Plastics Economy

Experts say that although taxes and bans designed to curb the volume of plastic getting into the world's rivers and oceans have helped the problem, the improvements have been incremental and piecemeal. More profoundly, they don't address the fundamental flaw of the linear economy of plastic. Once used, plastic waste has no value and ends up as landfill, in the incinerator, or the environment, rather than being reused or recycled within a circular economy.

In a March 2018 report for *C&EN*, Alex Scott explains why markets for plastic waste don't exist. "Once plastic waste is combined in the postconsumer waste stream, most of the characteristics valued in individual plastics—such as elasticity, finish, color, and strength—are lost. And it can cost more to use recycled feedstocks than virgin petrochemical ones." Scott writes, "In an attempt to fix this disincentive and a plethora of inefficiencies involved in collecting and sorting plastic waste, in January the European Commission introduced its first Europe-wide plastics recycling plan."[102]

Scott says that "the bottom line of the EC's new plan is that by 2030, all plastic packaging used in the region should be recyclable. By the same date, the EC wants to recycle 55% of plastic packaging waste, which makes up about two-thirds of all plastic waste generated in the region. To meet these targets, the EC aims to introduce new standards for plastics that simplify the recycling process. 'The problem is that now we have too many different plastics that, when put together, are not easy to separate or recycle,' Jyrki Katainen, the commission's vice president for jobs, growth, investment, and competitiveness, said at a recent conference in Brussels."

The EC's plan mirrors an approach laid out by "The New Plastics Economy," a January 2016 report by the Ellen MacArthur Foundation.[103] In a 2016 *C&EN* cover story, Alex Tullo writes "Industry ownership of the problem is a big part of the "New Plastics Economy" report. The emphasis is on a circular economy, in which the industry cultivates a supply chain for used materials so they will be reused—ideally in their original, high-value applications. The report calls on industry to simplify the materials it uses in multilayer packaging. It suggests a "search for a 'superpolymer' with the functionality of today's polymers and with superior recyclability."[104]

In addition to recycling, a circular plastics economy requires scrupulous collection of waste. Waste collection is the theme of "Stemming the Tide: Land-Based Strategies for a Plastic-Free Ocean," a 2015 report from the Ocean Conservancy, an NGO. The report identifies China, Indonesia, the Philippines, Thailand, and Vietnam as the primary contributors to more than half of ocean plastics.[105] In a 2018 *C&EN* cover story, Alexander Tullo writes that the Ocean Conservancy report "maintains that these five countries could reduce plastics litter to the ocean by 65% as early as 2025, reducing overall marine plastics leakage by 45%. The effort would cost $5 billion annually. The essence of the plan is that towns and cities need to collect more garbage from residents. Ocean Conservancy estimates that 75% of plastics leakage comes from uncollected waste. The other 25% of the leakage comes from cracks in the waste management system itself, the NGO says. This happens, for example, when an open-air dump is located near a river, allowing plastics to blow into the water. Remedies include better landfills, recycling, and waste-to-energy facilities where combustion can take plastics out of circulation for good."[106]

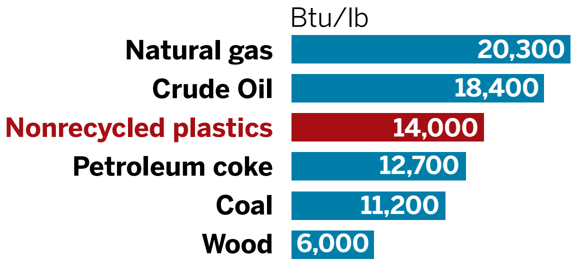
Any plastic that is not collected or recycled will eventually escape into the environment, so some experts have called for materials that are non-toxic and degrade easily. In a recent study in *ES&T*, Jason McDevitt proposes a framework for a standard which he calls "Ecocyclable." McDevitt's standard stipulates that an "Ecocyclable" plastic will lose at least 75% of its mass after a 180-day exposure in the environment, that the material will not bioaccumulate, and that the plastic's toxicity will be equivalent to that of either cotton fiber or poly-3-hydroxybutyrate, a biodegradable plastic produced by bacteria.[107]

Sustainable Plastics

Chemistry and biotechnology have a huge role to play in remediating the planetary burden of plastic discards and creating a new generation of degradable plastics. Companies are increasingly regarding plastic discards not as trash, but as a valuable resource to be mined. As *C&EN* reported in 2014, entrepreneurs "are trying to solve the plastic waste problem and at the same time harness the energy that for decades has been buried at the dump. These people are using pyrolysis to break polymers apart and turn them into synthetic crude oil and other hydrocarbons." One process heats plastic trash to 800°F under low-oxygen conditions to form hydrocarbons akin to light, sweet crude oil. A ton of plastic contains the energy of about 5 barrels of oil.[108]

Energy Sources

Plastics offer more energy per pound than does wood or coal.



Source: Columbia University Earth Engineering Center
Credit: Columbia University Earth Engineering Center

Reprinted in part from: *C&EN* 2014, *92*(9): 32-33.

Companies have also begun to transform trash into products. A *C&EN* cover story this year reports that the Dell computer company "used about 7 metric tons of plastics that had been dumped in Port-au-Prince, Haiti, to create packaging for its XPS 13 laptop. The company aims to increase usage 10-fold by 2025." Dell then created a model "to pinpoint hot spots in Asia where it could find sources of plastics. Oliver Campbell, the firm's director of worldwide procurement and packaging, says the technique isn't unlike the seismic imagery an oil company might use to decide where to set up a rig. 'We weren't drilling for oil; we were drilling for ocean plastic,' he says."[109]

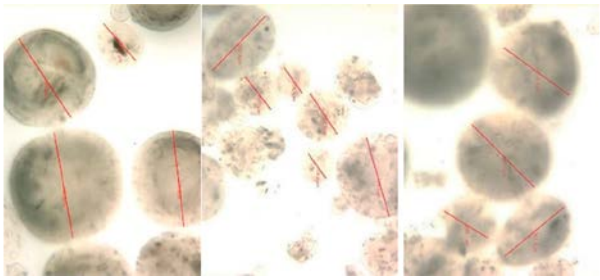
Recyclers can turn discarded water and shampoo bottles made from PET into carpet and construction materials. Yet, as Melissae Fellet wrote in *C&EN*, "some of these products cannot be recycled again and eventually end up in landfills or the environment. By using enzymes to break PET into ethylene glycol and terephthalic acid, recyclers could use the recovered ingredients to make new plastic bottles of the same quality. Bacteria that cause plant diseases use an enzyme called cutinase to destroy polyester linkages in the tough outer coating of plants. In previous studies, researchers discovered that cutinase can also digest PET and break it down into its monomeric ingredients." Fellet describes how Richard A. Gross of Rensselaer Polytechnic Institute and colleagues added sugars to a cutinase enzyme to keep it folded at high temperatures and therefore was able to degrade more PET than the conventional enzyme.[110]

A few years ago, researchers examining a Japanese recycling center stumbled onto a bacterium that uses an enzyme called PETase to degrade PET plastics into ethylene glycol and terephthalic acid. Hoping to determine the enzyme's structure, scientists at the National Renewable Energy Laboratory obtained high-resolution X-ray crystal structures of PETase. The native enzyme's activity is too low for industrial use, but the researchers mutated the enzyme, increasing its efficiency by 20%. The team plans to improve the enzyme and eventually use it on an industrial scale.[111]

In an ideal world, we could have our plastic and let the microbes eat it when we're done. To that end, manufacturers have responded with a range of degradable plastics that raise some surprising complications. For example, in the early 2000s, supermarkets began providing oxo-degradable shopping bags designed to disappear quickly when exposed to sunlight. Oxo-degradable plastics are made of common polymers such as polyethylene blended with metal-based additives to speed their breakdown. The problem is that these materials rapidly break down into harmful microplastic particles that take decades or more to fully decompose.[112]

At first glance, plant-based plastic seems like a better option. The two most common bio-based plastics are bio-polyethylene produced from biomass feedstock and poly(lactide), a polyester made from corn and sugar cane. Theoretically, these materials could rapidly degrade under microbial activity to carbon dioxide, methane, and water, a process known as mineralization. But the speed at which the plastics degrade is dependent on environmental conditions. Furthermore, depending on the feedstocks used, bio-based plastics could generate more greenhouse gas emissions than petroleum-derived plastics.[113] And if they are discarded into the recycling stream, they would need to be separated from all other plastic discards. Stephan Kubowicz says in a recent study, "Importantly, when they are mineralized in industrial composting facilities this represents the loss of a potentially useful resource that fails to meet societal goals for a circular economy."[114]

Researchers are delving into the development of benign substitutes for plastics. A recent study in *ACS Sustainable Chemistry & Engineering* explores the use of chitin as an alternative to synthetic microbeads. Chitin, found in crustacean shells, is naturally biodegradable and non-toxic. The scientists extracted chitin from shrimp shell waste and used an ionic liquid and polypropylene glycol to prepare the porous microbeads. The researchers obtained control of the bead size in a process suitable for commercial scale-up.[115]



Optical microscopy images of IL-extracted chitin beads, showing fractions with different sizes: left >350 μm; middle <125 μm; and right 125–250 μm.

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Because so many food and beverage containers consist of multiple layers of different materials, sometimes including a thin layer of aluminum, they are nearly impossible to recycle. Solving this problem has become a priority for the Ellen MacArthur Foundation, which has funded the Circular Materials Challenge, a prize aimed at making all packaging recyclable. One of this year's winners, the University of Pittsburgh's Eric Beckman, proposes to compose each layer of the packaging from the same material, polyethylene. Using nano-manufacturing, he will manipulate polyethylene molecules so that each layer will perform a specific function, yet at the end of use will be fully recyclable.[116]

VI. CONCLUSION

The painstaking work of scientists has helped bring plastic contamination into public consciousness. It is difficult to go more than a week without hearing about a new discovery, process, or idea. Some observers have predicted that 2018 will be a watershed year for action on plastic debris. At the World Economic Forum in January, Canadian Prime Minister Justin Trudeau announced that Canada would use its G7 presidency this year to focus on plastic waste reduction. In March, the Canadian Press interviewed Environment Minister Catherine McKenna, who said, "We are looking at a zero-plastics-waste charter." She added that the charter could go further than the EU's plan to recycle at least half of its plastic packaging by 2030.[117]

Meanwhile, chemists, engineers, and environmental scientists play a crucial part in informing policy change and mitigation. Plastic contamination is a relatively new field of inquiry, wide open for scientific advances at all levels. There is a need for improved sampling and analytical techniques, better understanding of the sources and fate of plastic debris and a greater knowledge of the impacts on ecosystems and humans. More research is needed to address the issue of the missing microplastic in the ocean, and not enough is understood about the biological processes and the timescales of plastic fragmentation.

Scientists have built a body of work that is beginning to paint a troubling portrait. Plastic litter penetrates every part of the planet and is abundant and increasing. Microplastics contribute the vast majority of particles by number, but not by weight. Entanglement of wildlife is well documented, some toxic effects on wildlife have been shown, but a major knowledge gap exists in whether microplastic affects human health. Virtually nothing is known about the presence and effects of nanoplastics in the environment.

Solving the plastic problem will be complex, yet there have been many encouraging developments in the past few years. It will take coordination among scientists, government officials, NGOs, and industry. With both science and policy around plastic waste rapidly evolving, it's an exciting time to be part of this dynamic field.

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